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Development of an unfired clay masonry system

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DEVELOPMENT OF AN UNFIRED CLAY MASONRY SYSTEM

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ABSTRACT

An unfired clay masonry system complete with renders and fixings was required for the mainstream construction of thin non-load bearing inner leaf or interior walls in domestic dwellings. A determined movement to reduce the impact the building sector has on the environment aims to incorporate natural materials such as earth, animal products and vegetable matter into the development of building products for the construction of domestic dwellings to produce sustainable modern buildings with minimal impact on the environment. An unfired clay masonry system is the most desirable system for the construction of earth walls in modern buildings. Masonry units are extruded quickly and consistently to satisfy the demands of mainstream construction. Walls are built in a manner similar to that of concrete block-work and fired-clay brickwork used in modern construction. Specifications and standards to satisfy modern building procedures and regulations can be more readily developed for the unfired clay masonry.

An investigation into the industrial extrusion of clay brick units showed that the unfired clay or green brick units were of strengths comparable to low strength materials used in the construction of thin non-load bearing walls. Suitable mortars for the unfired clay brick units were developed directly from the respective brick clays. The unfired clay mortars gave strengths and bond strengths required for the construction of thin walls with the addition of sodium silicate and the use of thin mortar joints. Unfired clay blocks extruded using brick clay representative of that most commonly used for the manufacture of fired-clay brick units gave good strengths. Masonry constructed using the unfired clay blocks and the respective sodium silicate unfired clay mortar gave good mortar strengths, mortar bond strengths, compressive strengths and flexural strengths. Compressive strengths and flexural strengths of the masonry were comparable to that of industrialised low strength buildings materials such as aerated concrete block masonry suitable for the construction of thin non-load bearing walls. The unfired clay masonry with un-mortared perpendiculars were however not suitable for the construction of thin non-load bearing walls.

Compressive strengths and flexural strengths of masonry constructed with a perforated unfired clay block format were substantially lower than those of masonry constructed with a solid unfired clay block format. Compressive strengths were suitable for the construction of thin non-load bearing walls but flexural strengths were not in particular the flexural strengths measured when loading perpendicular to the bed joints. Wood-fibre significantly improved the strength and toughness of the unfired clay masonry and a similar perforated wood-fibre block significantly improved the flexural strength perpendicular to the bed joints giving masonry of the desired flexural strengths. Adding wood-fibre into the extrusion process was problematic but a successful procedure was developed to incorporate the wood-fibre into the brick clay mixture prior to extrusion.

Moisture significantly influenced the strength of the unfired clay masonry. At ambient conditions the strength of the unfired clay masonry is adequate but at higher moisture contents the strength decreases and exposure to water or constant exposure to very high levels of relative humidity could significantly lower the strengths of the unfired clay masonry.

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CHAPTER 1

INTRODUCTION

1.1 Background

Earth is one of the earliest building materials known to man. A large number of people throughout the world still live in earth buildings and nowadays many dwellings are still being constructed using earth. In developing countries earth is often considered to be a building material of the poor and not as structurally sound as modern building materials. The trend in developing countries is to build houses with materials such as fired brick and concrete block. Modern architectural design has challenged both these critiques. Many homes in developed countries have now been built with earth, which are as if not more impressive than those built with modern materials. Innovative design techniques used ensure the earth structures are protected from the elements which render them unsound (Houben and Guillaud, 2008).

A major advantage of earth is that it is a natural product. It is reusable, recyclable and can be disposed of with minimal impact on the environment. It is also low in embodied energy and embodied carbon. Owing to its use in modern builds and its low impact on the environment earth is slowly re-emerging as a modern building material. Unfortunately most modern houses being built with earth are expensive and satisfy a niche market. In addition, adobe, cob and rammed earth, which are the techniques mainly employed in modern earth builds, are slow and not suitable for mainstream construction. A material such as unfired clay masonry which can compete against fired brick and concrete block masonry is required to ensure earth is considered for mainstream construction. Methods such as extrusion and compression can be employed to mass produce the unfired clay units with consistent properties and a mortar can be developed from the clay used to manufacture the masonry units.

A natural building material has many advantages but as with all products there are also disadvantages. An area where natural materials can have a huge impact is the housing sector which is a major contributor to global warming and consumer of natural resources. Although the operational energy is the main contributor to a buildings energy consumption and carbon emission over its entire life cycle, it is significantly reduced with the use of super-insulated walls and windows. As a result, a general oversight is to disregard the energy required for the production of these modern building materials and components and that required for the demolition and recycling of the building that is the pre-use energy and post-use energy respectively. As the operational energy of building is reduced the lowering of the embodied and post-use energy becomes more critical in reducing the overall energy usage of the building.

Clay and plant fibres are fine examples of natural materials that can be used to develop building products and components of low embodied energy and embodied carbon. With some modifications they can replace the high embodied energy/carbon materials used to manufacture the building products and components developed for modern mainstream construction. One alternative is to use unfired clay units instead of the conventional fired clay units for the construction of non-load bearing inner walls. An unfired clay unit is of a substantially lower embodied energy (0.44 MJ/kg) and embodied carbon (0.03 $kgCO_2$/kg) than the fired clay units (3.00 MJ/kg and 0.24 $kgCO_2$/kg respectively) (Greenspec® online, 2010). Incorporating the plant fibres into the unfired clay units improves durability and gives the unit more value. Another advantage with the use of unfired clay, which is arguably the most important, is that it controls the humidity within modern super-insulated homes to levels which stifle the growth of dust mites a major contributor of allergens causing respiratory illnesses such as asthma (Howieson, 2005).

The research documented in this report resulted from a partnership formed between Kingerlee Ltd (The Industrial Partner) and the University of Bath (The Academic Partner). The partnership received financial support from the Knowledge Transfer Partnership (KTP) programme. The programme aims to improve the competitiveness and productivity of businesses utilising knowledge, technology and skills that exist within the UK Knowledge Base. The programme is funded by the Technology Strategy Board and other government organisations. The sponsorship was granted on the basis of a strong case proposed by Natural Building Technologies (NBT) a subsidiary company of Kingerlee. NBT aims to become the leader in the supply and manufacture of environmentally friendly building products in the UK. The main focus of the company is to market building products made from natural materials and to ensure the building products are reusable, recyclable and degradable. While not directly contributing to the project, Ibstock Brick Company supplied materials and made their plant available for use for the project.

1.2 Objective and scope of the research

The objective of the research was to develop an unfired-clay block masonry system, including finishes and fixings, for mainstream construction in the UK. The aim was to attain an environmentally friendly, recyclable masonry system to replace conventional fired-clay brick and concrete block systems currently used for the construction of thin (± 100 mm) non-load bearing inner walls. An unfired clay block of dimensions similar to that of the standard concrete blocks (440 mm × 215 mm × 100 mm) used in mainstream construction and a thin mortar joint (approximately 3 mm thick) was desired. The scope of the research was to:

- conduct a literature survey
    - gain a background into earth building particularly in work done with unfired clay
    - identify tests to determine suitability of unfired clay for the construction of walls
- determine whether extruded unfired clay brick units manufactured in factories that produce conventional fired clay brick units are suitable for the construction of thin non-load bearing inner walls
    - identifying factories suitable for the production of unfired clay block units
    - assess properties brick clays and of the respective unfired clay brick units
- develop mortars suitable for the construction of thin non-load bearing unfired clay walls
    - assess properties of mortars
    - determine mortar application methods

- modify the brick clays used for extrusion to give value to and to improve on the properties of the extruded unfired clay units
- develop prototype block units
    - organise production of prototype block units
    - assess properties and durability of prototype block units
- determine whether the unfired clay masonry system developed is suitable for the construction of thin non-load bearing inner walls
    - assess properties of wall panels built with the prototype block units and mortars
- identify renders and fixings for the unfired clay masonry system
    - determine adhesion of renders onto the wall panels
    - measure strength of fixings into the wall panels
- determine unfired clay block format for mainstream production
- identify mainstream production methods for the unfired clay blocks

1.3 Limitations of research

The limitations of the research were governed by:-

- properties of the unfired clay
- type of product desired
- difficulty in obtaining plant fibres
- manner in which bricks are extruded
- a poor economy
- limited timescale for research

Owing to the low compressive strength of unfired clay and the sharp reduction in compressive strength associated with the absorption of moisture, the research was limited to finding a masonry system for the construction of non-load bearing inner walls. An environmentally friendly and completely recyclable product which on disposal would have minimal impact on the environment was desired. The research was therefore limited to using natural additives such as plant fibres to stabilise and improve on the properties of the unfired clay. Shortages of plant fibres in the UK, cost of fibres, cost and energy associated with transport/import of fibres and cost of processing fibres into the desired form limited the investigation and only straw, flax, hemp and wood fibre were considered. Wood fibre, which proved most suitable, was scarce in the UK and the fibre needed to be imported from within the EU.

The extrusion process used to produce fired clay bricks is relatively straight forward and offers little flexibility with regard to modification to allow the addition of materials such as plant fibres into the brick clay. Mixing of the fibre at the plant was difficult and led to blockages and downtime. As a result only three different types of prototype blocks were produced instead of the six desired for the investigation. Any further trials required plant fibres to be mixed into the brick clay off site which could only be done on a small scale and this prevented the running of a trial to produce the block format envisaged for mainstream production. In addition to the difficulty in obtaining plant fibres and the inflexibility of the brick plants to produce the prototype blocks a poor economy which significantly impacted on the building industry also limited the overall progress of the investigation. The plant originally identified for the block trials was shut during the project which caused considerable delays. Additional testing was required to ensure brick clays at other plants could be used to develop the prototype blocks and mortars.

1.4 Outline of thesis document

A literature survey (chapter 2) follows this introductory chapter discussing:-
- traditional earth building methods
- modern earth construction and the use of unfired clay blocks
- soils and soil analyses
- soil stabilisation and use of natural materials
- advantages to the use of natural materials
- standard test methods to determine properties of masonry
- the brick extrusion process

Chapter 3 discusses the development of the prototype unfired clay block units and entails:-
- a preliminary investigation into the characteristics of extruded unfired clay units
- analysis of various brick clays and brick units from the brick plants identified
- modifications of the brick clays with plant fibres to improve on properties of unfired blocks

Chapter 4 deals with the development of the mortar for the unfired clay masonry discussing:-
- preparation and mixture proportions
- bond strengths
- application methods
- addition of plant fibres

Chapter 5 discusses the prototype block trial and documents the results from tests done on masonry made from the prototype blocks and mortars produced:-
- appearance of blocks
- properties of blocks
- compressive and flexural strengths of wall panels
- mortar bond strengths
- further trials to identify production of desired block format

Chapter 6 documents the conclusions and discusses the limitations of the research and the future research requirements.

1.5 Definitions

Additive: A material used to improve the characteristics of earth

Adobe or mud brick: Sun-dried, hand-made earth blocks

Brick: A discreet unit of earth masonry either shaped in moulds by hand or machine, extruded or compressed into moulds

Characteristic strength: An estimate of the lower 5 % value with 75 % confidence from tests on a representative specimen

Clay: A fine grained (less than 0.002 mm) natural earth material composed primarily of aluminium silicates

Cob: Wet lumps of earth progressively stacked in courses and shaped by hand to from a monolithic wall

Cohesion: Stickiness characteristic of clay and silt

Compressed earth brick: An earth brick made in a mechanical press

Compressive strength: A physical property measuring the materials ability to resist compressive forces or loading

Concrete block: A masonry unit made by casting concrete into moulds

Durability: Resistance of a material to wear and decay

Earth or soil: Natural sub-soil consisting of varying percentages of clay, silt, sand and gravel which is unfired and free of organic matter

Eaves: Edge of a roof which projects beyond external walls

Erosion: Physical and chemical processes including weathering and mechanical wear by which earth building materials are worn away

External wall: An outer wall of a building

Fired clay brick: A fired clay brick masonry unit (see brick)

Flexural strength: A physical property measuring the materials ability to resist lateral forces or bending

Formwork: Temporary support used in rammed and poured earth construction

Foundation: Base that supports the building

Inner wall: An inner wall of a building forming a partition to separate rooms or inner leaf to an outside wall

Green brick: an unfired clay brick masonry unit prior to firing (see brick)

Load-bearing wall: A wall supporting vertical loading from floors, ceiling joists or roof in addition to its own self weight

Masonry unit: Rectangular prism usually bonded together by mortar to construct walls

Mortar: The bedding material on which masonry units are bedded and bonded

Non load-bearing wall: A wall other than a load-bearing wall not supporting any major structural loads

Perpendicular or perpend: Vertical joint between adjacent masonry units in the same course

Pored earth: A building technique in which a mixture of earth and water with or without additives are pored into moulds to form a wall

Rammed earth: A building technique in which moist soil with or without additives is tamped into formwork to form a wall

Render: Material used to plaster walls for decoration and moisture resistance

Sand: Fine individual rock or mineral particles in soil (0.06 mm to 2.0 mm)

Shrinkage: Decrease in volume of earth material due to the evaporation of water

Silt: Fine individual particles in soil (0.002 mm to 0.06 mm)

Stabilisation: Adding materials to earth to improve properties or performance of earth building materials

Structural wall: Any wall which contributes to the rigidity and strength of a building

1.6 References

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Modern earth building is becoming more recognised worldwide. This is due to the need to construct buildings that have a lower impact on the environment throughout their entire life cycle, that is from cradle to grave (extraction and manufacture to eventual deconstruction and disposal of building materials), and the numerous other advantages building with earth has such as improvement in comfort and health factors associated with modern insulated buildings. Countries, for example New Zealand and 15 of the 16 states in Germany, have implemented standards for earth building and research of an empirical nature is being done in numerous establishments worldwide to develop earth building materials for modern and even mainstream construction. Although the drive exists to develop natural products such as earth and plant fibres as modern building materials they are far less researched than conventional building materials such as cement and concrete.

Earth has been used as a construction material for over 10 000 years, that is ever since man has been building homes, making it one of the most widely used construction materials in the world (Houben and Guillaud, 2008). The same technology and science can be used in building with earth as with other construction materials. The use of earth is unlimited if users are aware of how to profit from its wide range of qualities and ameliorate its defects.

The objective of the literature review was to gain an understanding into traditional earth building practices and review modern earth building practices in particular that relating to construction using earth bricks or blocks such as unfired clay masonry units which are used in mainstream construction. Traditional earth building practice and techniques are well documented. Work published with regard to modern earth building mainly relates to rammed earth, adobe and compressed bricks. A limited amount of literature is available describing the use of earth bricks or blocks in modern construction particularly with the use of these units for mainstream construction both of which are the objectives of this research.

The scope of the literature review was to:

- define soil in terms of origins, classification and phases
- review soil identification techniques
- gain and insight into soils used for construction
- develop a basic understanding in traditional and modern earth building
- recognise the potentials of earth as a building material
- identify ways of avoiding the misuse of earth in construction
- identify laboratory test methods required for soils and earth masonry
- gain an understanding into the sustainability, embodied energy, embodied carbon and life cycle analyses of buildings and building products
- identify processes for the manufacture of clay bricks

2.2 Origins, classification and phases of soil

Soil results from the deterioration of underlying rock by physical, chemical and biological processes. Sun, rain, frost and wind crack, break-up and dissociate the underlying rock forming stone, gravel, sand and silt. Animals, plants and micro-organisms generate chemical and organic substances resulting in the formation of clays, minerals and chemicals. A homogeneous soil results in which minerals and chemicals migrate enriching the soil forming distinct layers or horizons (Houben and Guillaud, 2008):

- a top layer rich in organic matter
- an elluvial layer poor in organic matter and colloids
- an illuvial layer containing colloids, iron and aluminium oxides and clays
- a base layer containing pieces of the deteriorated parent rock

Soils are classified as (Houben and Guillaud, 2008):

- organic soils mainly contain decomposed organic matter
- gravel soils mainly contain gravel particles (2 mm to 20 mm in size) and round/angular pebbles (20 mm to 200 mm in size)
- sandy soils mainly contain rounded sand particles (0.06 mm to 2 mm in size)
- silt soils mainly contain rounded particles (0.002 mm to 0.06 mm in size)
- clayey soils mainly contain clay plate-like alumino-silicate particles, colloidal particles and agglomerates

Soils have a solid, liquid and air phase. The solid phase consists of organic matter (i.e. animals, plants, micro-organisms, animal waste and decomposed vegetation) and mineral matter (stone, gravel, sand, silt, colloids and clay). The solid phase determines the structure of soil (i.e. loose, crumbly or continuous) and influences the physical properties of the soil such as air and water circulation. The water or liquid phase contains sugars, alcohols, organic acids, acids and bases and salts of calcium, magnesium, potassium, sodium in form of phosphates, sulphates, carbonates or nitrates. The gas/air phase consists of nitrogen, oxygen, carbon dioxide, hydrogen and methane.

2.3 Soil identification techniques

Soil identification is important in traditional earth building as earth is not a standardised building material such as industrial building materials like concrete and fired brick. Soil is sourced locally and often from the soil dug-out on site for the foundation. Clay, silt, sand and aggregate contents vary from site. As a result, soil characteristics change and mix designs need to be corrected to ensure the mixture suits the specific application method.

2.3.1 On-site identification techniques

A few simple field examinations can be done to categorise the soil type. A visual examination gives an estimate of the sandy and fine fractions of a soil. Smell identifies organic matter. Nibbling indicates if the soil is sandy (grinds teeth disagreeably), silty (grinds teeth with no disagreeable sensation) or clayey (smooth floury sensation) (Houben and Guillaud, 2008). Soil can be further classified using some rudimentary field procedures on soil that is moistened after removing the particles greater than 2 mm in size (Houben and Guillaud, 2008):

- Sandy soil easily rinses off when rubbed over hands. Silty soil is powdery and hands rinse clean without great difficulty. Soil which is clayey is sticky and difficult to rinse off.
- Sandy soil appears rough with no cohesion when rubbed between fingers or palm of hand. Silty soil has slight roughness and is moderately cohesive. Clayey soil forms lumps and becomes sticky.
- Soil is formed into a ball and then cut with a flat blade/knife or spatula. A dull surface indicates a silty soil and a shiny surface a clayey soil. Soil is extremely clayey if it is difficult to insert the knife and the soil sticks onto the knife on removal. If insertion of the knife is not difficult but the soil sticks to the knife on removal it is moderately clayey. If no resistance is felt on inserting the knife the soil has low clay content even if the knife is dirty on removal.

A more robust field test is used to assess soil texture, size of different fractions and quality of the fine fraction (Houben and Guillaud, 2008). Soil and water is added to a 1 ℓ jar (1 part soil to 3 parts water) with opening through which the hand fits and thoroughly agitated by shaking. Soil is allowed to settle for approximately 8 hours and the sedimentation of the various grain portions is measured (layers from top to bottom - organic matter, colloidal suspension, clay, silt, sand and gravel) and the percentage of each grain fraction is calculated. A number of tests are then conducted on the particles less than 0.4 mm in size collected from the sediment and which is dried:

- Dry strength test: Three moist pats of soil are prepared and dried in the sun or oven. The pats are broken and pulverised between the thumb and index finger. If the pats snap and crumble but cannot be crushed to dust the fine fraction is high in strength and almost pure clay. A silty or sandy clay fraction gives a pat of moderate strength which is quite easy to break and requires little effort to crush into powder. Silt or fine sand with a low clay content give rise to pats which are easily broken and crushed into a powder.
- Water retention test: A moist ball (2 - 3 cm in diameter) that does not stick to fingers is prepared. The ball is flattened slightly, then slapped to draw out water and finally pressed flat between thumb and index finger. A very fine sand or coarse silt fraction requires 5 to 6 blows to bring water to the surface. The water disappears when pressed and the ball crumbles. A slightly plastic silt or silty clay requires 20 to 30 blows to bring water to the surface. On pressing the ball flattens without cracking or crumbling. With a clayey soil no water appears on surface when patted and on pressing the ball remains shiny.
- Consistency test: A ball (2 cm to 3 cm in diameter) is prepared. Water is then added to enable rolling of the ball into a thread on clean smooth surface which breaks when a diameter of 3 mm is reached. It is then reshaped into a ball and crushed between the thumb and index finger. A fines fraction with high clay content is difficult to crush and does not crack or crumble. One with low clay content cracks and crumbles. If the fraction has a high sand or silt content and very little clay the thread cannot be reshaped into a ball without cracking or crumbling. For organic soil the thread and reshaped ball has a spongy feel.
- Cohesion test: A 3 mm diameter thread as above is prepared from the fines fraction and carefully flattened between index finger and thumb to from a ribbon 3 mm to 6 mm wide. The length of the ribbon prior to breaking is measured. A fraction with high clay content gives a long ribbon (25 cm to 30

cm), one with low clay content gives a short ribbon (5 cm to 10 cm long) and one with very low clay content cannot be moulded into a ribbon.

2.3.2 Standard laboratory soil tests

Standards exist to accurately analyse and define the characteristics and properties of the soils. Such robust test procedures are necessary to ensure the right mixture designs and modifications are done on the soil intended for traditional earth building but are essential in modern earth construction which aims to use products that fulfil the requirements in standards stipulated for industrialised building materials and construction techniques or similar standards that have been specifically developed for earth building.

Soil test methods of importance to earth building are similar to those documented in the British Standard – Soils for civil engineering purposes (BS 1377), which are described below. Not all the standard soil tests listed below were necessary for this investigation, The soil tests relevant to this investigation are those listed in the standard classification test document (BS 1377-2:1990) namely those to determine moisture content, plastic index (i.e. derived from liquid and plastic limits measured), shrinkage characteristics and particle size distribution.

Shrinkage depends on the composition and moisture content of the soil and gives an indication of the contraction of a soil on drying, which is an important characteristic to consider with the construction of earth walls, for example, a clayey soil with excessive contraction can lead to cracking. Plasticity, which is expressed as the plastic index of a soil, is related to the moisture content and cohesiveness of the soil and measures the deformation of the soil without cracking or disintegration. Plasticity indicates whether a soil is suitable for certain types of earth construction, for example, the manufacture of unfired clay masonry units such as the extrusion of clay bricks. Particle size distribution indicates whether the soil is suitable for the type of earth construction intended, for example, if there is sufficient clay and silt for use in the manufacture of clay bricks.

1. Standard classification tests (BS 1377-2:1990) are done on a specimen prepared from a representative soil sample collected (BS 1377-1:1990) to determine:

- moisture content - amount of water in a sample of soil expressed as a proportion by mass of the dry soil particles when the mass of the soil sample remains constant on drying in an oven at 105 °C
- liquid limit (w_L) - moisture content at which the soil resists shearing i.e. passes from its liquid state to its plastic state)
- plastic limit (w_P) - moisture content at which a soil becomes too dry to be plastic and becomes brittle and plastic index (I_P) – derived from the w_P and w_L (i.e. $I_P = w_L – w_P$) which when plotted against the liquid limit on the plasticity chart (BS 5930:1999+A2:2010) provides a means of classifying cohesive soils
- shrinkage characteristics (i.e. volumetric and linear shrinkage) - shrinkage limit (w_s) of clays (i.e. moisture content below which a clay ceases to shrink on drying or expand on wetting)
- density

- specific gravity or particle density
- particle size distribution - wet or dry sieving method on particles greater than 63 µm in size followed by a sedimentation analysis on the particles less than 63 µm in size to determine particle size fractions and plot a grading envelope

2. Chemical and electrochemical tests (BS 1377-3:1990) are done on soils to determine any impurities that would render them unsuitability for earth construction and manufacture of masonry units:

- organic matter content - dichromate oxidation of soil sample and titration against ferrous sulphate
- mass loss on ignition - related to the organic content of certain soils (i.e. sandy soils containing a negligible clay or chalky material, peat and organic clays containing more than about 10 % organic matter)
- sulphate content – natural acid soluble sulphates such as calcium sulphate using gravimetric analysis (i.e. titration against barium chloride to precipitate barium sulphate which is collected and weighed to determine sulphates)
- carbonate content – soil sample mixed with hydrochloric acid which reacts with carbonates to form carbon dioxide treated (rapid titration method used for soils of carbonate content greater than 10 % is treated with a known quantity of acid and excess acid is determined by titration against sodium, gravimetric method carbon dioxide evolved is passed through a granular absorbent which enables the mass of carbon dioxide to be determined)
- chloride content - water soluble chlorides dissolve soil sample in water and add silver nitrate to precipitate silver chloride, acid soluble chlorides dissolve soil sample in dilute nitric acid and add silver nitrate to precipitate silver chloride

3. Compaction tests (BS 1377-4:1990) to determine characteristics relating to the compaction of soils. Solid particles of the soil are packed more closely together during compaction increasing the dry density of the soil, which depends on the degree of compaction applied and on the amount of water present in the soil. The optimum moisture content (OMC) for a given degree of compaction and a given cohesive soil is that at which the maximum dry density of the soil is obtained (i.e. for a given soil an increase in compaction energy increases dry density and reduces the OMC). OMC and dry density are also determined using the Proctor Compaction Test documented in the American Society for Testing and Materials standard (ASTM D698 - 07e1 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort). These tests are more appropriate for rammed earth than other forms of earth construction as the process of forming rammed earth is similar to that in the compaction tests.

2.4 Soil for construction

Soil properties namely size and distribution of particles, plasticity, compressibility and cohesion determine whether the soil is suitable for construction. A soil of good inherent cohesion containing 5 % to 20 % clay is generally suitable such as subsoil of various geological origins containing no organics and topsoil (Houben and Guillaud, 2008).

Compaction of the soil is important. Compaction minimises the gas phase which restricts growth of micro-organisms, diminishes water penetration and improves strength. Cohesion of the soil (capacity of soil grains to remain together when under tension) depends on the thickness of the soil solution film and the substances/elements dissolved in the film and the cementation properties of the mortar (i.e. clay, silt and sand particles less than 2 mm in size). The smaller the particles the stronger the cohesive forces (strengths are similar to forces in crystalline minerals for particles less than 2 mm in size and to inter-atomic type chemical bonds in three dimensions for particles less than 2 μm in size) (Houben and Guillaud, 2008).

Clayey soils are of particular importance in modern earth building namely in unfired clay masonry where units are in the form of either handmade adobe or mud bricks, extruded green bricks (i.e. extruded unfired clay bricks prior to firing) and compressed earth blocks. Clayey soils are cohesive, sticky and malleable.

Clayey soils result from the chemical weathering of rock to form clay molecules which are either negatively or positively charged. The molecules are plate-like in shape and held together by electrostatic forces. Orientation of the bonding is either surface to side, side to side or surface to surface. The bonding form sheets of clay molecules that give rise to either tetrahedral silica layers or octahedral alumina layers. Quartz and feldspar form the skeleton of clayey soils and if in contact highly resists deformation.

Clay exists in nature as kaolinite, illite or montmorillonite. Kaolonite is a two layered structure composed of a silica tetrahedron layer and an alumina octahedron layer which is stable in water. Illite is a three layered structure of an alumina octahedral layer between two silica tetrahedral layers which is not stable in water. Montmorillonite is a structure similar to illite but where the aluminium ions in octahedron layer are substituted by magnesium, iron, nickel or manganese ions which swells severely in water.

Clayey soils have different states which depend on the moisture content, film of water between the particles, size and shape of the particles and chemical make-up of the particle surfaces:

- solid state requires powerful kneading to form a ball which flattens slightly when dropped from height of 1 m
- semi-solid state requires slight kneading to form a ball which flattens slightly without disintegrating when dropped from a height of 1 m
- semi-soft state is neither sticky nor soiling and easy to shape into a ball which flattens markedly without disintegrating when dropped from a height of 1 m
- soft state is sticky and soiling and cannot be shaped into a ball
- muddy state is a viscous, liquid mass of soil

Clayey soils are best defined in terms of its plasticity which is the ability of soil to deform without cracking or disintegrating. Plasticity is measured in terms of the plastic index which as described above depends on the liquid limit (i.e. between the soft and mud states) of the soil and plastic limit (i.e. between the solid and semi-solid states) of the soil.

2.5 Construction of traditional earth buildings

A well designed traditional earth building aims to minimise or eliminate effects of bad weather, unhealthy conditions and deterioration. An earth building as with all buildings requires a good foundation, a good roof and good walls. Walls built from earth have a water resistance substantially lower than that of concrete and fired brick and therefore it is essential to have a good roof and foundation to minimise or eliminate contact with water such as driving wind and rain, water splashing, water ingress from the top, rising damp and moisture generated internally. The deterioration of earth walls depends on severity of wind-driven rain, orientation of wall to the bad weather, weather resistance of the wall as well as stabilisation of the soil material used, surface finishes and coatings.

The foundation must be a solid, water resistant structure such as concrete, stone, fired brick or rubble. It must be constructed on solid ground to avoid movement that causes tension, bending and shear in walls. The height above ground must be sufficient (20 cm) to prevent water damage from rain, splashing, standing water and flooding. There must be good drainage of the surface water from the surrounds. Water infiltration must be eliminated and proper drying out must be ensured. A roof must have adequate eaves to protect the earth walls from the elements. Good design of openings, parapets and sills is required. The bonding between different materials must be sound (Houben and Guillaud, 2008).

2.5.1 Construction of earth walls

A diverse range of techniques exist for the construction of earth walls. A good wall must have adequate strength in compression and tension in the wall must be avoided. Walls constructed are either monolithic walls or walls made from individually laid bricks namely:

1. Adobe or mud-brick – air dried earth-brick made from a mixture of mud and chopped straw cast in wooden or metal moulds
2. Rammed earth – moist earth compacted into formwork
3. Straw-clay – very clayey soil dispersed in water to form a greasy slip to which chopped straw is added as a binding agent to form bricks, insulating panels or flooring blocks
4. Wattle and daub - wooden structure filled with a daubed lattice or netting of woven vegetable matter such as straw which is then filled and covered with an extremely clayey soil
5. Direct shaping - shape/model a plastic soil into various forms for example dam walls
6. Compressed earth blocks - compress or tamp earth mechanically or by hand into solid cellular or hollow bricks, flooring or paving elements
7. Cob - earth balls reinforced with fibres such as straw, grass or twigs are shaped by hand and then placed on top of one another and tamped using hands and feet to form walls

Wall strength, deformation and damage depend on the standard of workmanship and in the case of earth brick walls the strength and durability of the individual components and their arrangements. Walls in traditional earth buildings must be made of a soil with properties suited to the building technique employed. Although a diverse range of techniques exist the one usually employed depends on the properties of the soil that is available locally. The process of earth building usually involves the following steps:

1. Locate suitable building site
2. Select preferred earth building technique
3. Consider suitability of local or nearby sub-soils for the various earth building methods
4. Conduct field tests on soils to check suitability for chosen construction method and modify or change method if necessary
5. Carry out testing of earth building material and modify mixture to suit construction requirements

Owing to the low strengths of earth building materials walls are relatively thick (greater than 300 mm) to achieve adequate strengths. Wall thicknesses are designed to be approximately 1/10 that of the wall height (Houben and Guillaud, 2008). Earth building materials are only suited for the construction of single or double storey dwellings were a downward thrust 0.1 N/mm^2 to 0.2 N/mm^2 is required and strengths of 10 N/mm^2 or more are not required (Houben and Guillaud, 2008). Materials strengths of 1.0 N/mm^2 to 1.5 N/mm^2 are the absolute minimum to avoid handling problems during building.

A good mortar is required for earth masonry. Strength of the mortar must be similar to that of the masonry units. A mortar can add up to 25 % in compressive strength and double the shear strength of a wall (Houben and Guillaud, 2008). Vertical joints must be mortared as unfilled vertical joints can result in a 20 % to 50 % decrease in compressive strength and no strength in bending and shear. The water content of the mortar must be low to minimise shrinkage and poor bonding which decreases the stability and strength of walls.

Walls must be built on a water resistant material extending at least 20 cm above the ground when foundations are below ground level. Walls must be breathable and allow the movement of moisture to avoid condensation on inner and outdoor surfaces and moisture accumulation on the inside of walls that may arise due to poor insulation and ventilation. Wetting of earth walls is not a problem but the penetration and accumulation of the water in the inside walls is as this is where the water causes decay in the earth walls.

Walls in traditional earth buildings are often improved with the use of stabilised soil or applying an external protection such as renders or coatings to isolate the walls from destructive elements.

2.5.2 Stabilisation of soil

Stabilisation aims to improve the properties of soil for construction. Soil is stabilised via modifications and/or additives and aims to (Houben and Guillaud, 2008):

- alter texture and structure
- improve cohesion
- improve dry and wet strength
- decrease porosity
- reduce shrinkage and swelling
- decrease permeability
- minimise surface abrasion

- improve water resistance

Soils are stabilised to increase strength either by refining (i.e. modifying to improve compaction), reinforcing (i.e. adding natural or synthetic fibres), adding cement, lime or mineral extenders (slag and fly ash) or chemicals such as synthetic or natural resins, salts and glues.

Soils are modified or refined by altering the texture of the soil such as removing or crushing coarse particles or mixing coarse and fine particles to get a preferred grading envelope. This improves the manner in which soils are compacted and increases the compaction effort.

Soils are reinforced by adding chopped or refined fibres usually up to 4 % by volume and 6 cm in lengths. Animal fibres namely hair and fur and plant fibre such as straw, wood, flax and hemp are used. The soil requires good mixing to scattered the fibres in all directions. Other advantages of fibre addition besides the improvement in strength include:

- prevent shrinkage cracks during drying
- accelerate drying
- increase absorption
- reduce density
- improve insulation
- improve compaction

Various chemicals such as acids, salts, flocculants, resins, mineral extenders or pozzolans are added to improve on particle flocculation, modify bonding between grains, repel water and waterproof the soil. Animal products such as excrement, blood, casein, glues from horns, bones or hooves, oils, fats and beeswax or vegetable products such as ashes, oils, fats, tannins, sap and latexes are also used. Water erosion tests on unfired clay bricks that gave surface disintegration after 4 minutes increased to 60 minutes for unfired bricks with a 30 % cow dung content and 7 days for unfired bricks with a 6 % cooked linseed oil content (Minke, 2007). Water basins were successfully developed from unfired clay with a 6 % cooked linseed oil content and from unfired clay with a 6 % addition of glue made from casein and lime (Minke, 2000).

Adding cement and lime to soil is not always beneficial. Cement and lime (6 % to 12 %) are generally added to increase strength and improve on water resistance of the soil (Houben and Guillaud, 2008). Silty loam mortars showed a decrease in compressive strength with a 2 % to 6 % addition of cement (i.e. from 2.2 N/mm^2 to 0.4 N/mm^2 when 2 % cement was added and to 0.8 N/mm^2 when 4 % cement was added) (Minke, 2007). Compressive strength also decreased with the addition of lime in similar quantities but not to such a great degree. Water absorption also increased with the addition of cement. A clayey sandy loam mortar which absorbed 2 ℓ/m^2/hr of water absorbed 24 ℓ/m^2/hr of water with a 2 % cement content and 7 ℓ/m^2/hour with 4 % cement content.

Other disadvantages of adding cement are the impact on the environment, that is the significant increase in embodied energy and embodied carbon of the earth materials preventing the decomposition of the earth materials on disposal creating a waste problem, and the significant increase in cost of the earth materials (a study showed that cement stabilised earth bricks were more expensive than fired bricks) (Minke, 2007).

2.5.3 Wall protection

Walls are rendered or coated to improve appearance and to extend the service life of walls by protecting them from harmful elements. Coatings and renders are also used to isolate external walls from bad weather and improve the impact resistance of the wall. Synthetic or natural coatings and renders are used. Coatings or renders must be chosen wisely as they hamper the movement of air and moisture through earth walls, are costly and increase the embodied energy and embodied carbon and restrict decomposition of the walls on disposal. Any applied coatings or surface finishes should provide permeability to prevent moisture from becoming trapped inside earth walls.

Cement and lime based renders are expensive and impact on the environment but they offer good protection and have been formulated to adhere to earth walls and allow movement of moisture and air through the walls. A fluorosilicate plaster also gives good protection. Natural coatings such as gum, resin and wax give good appearance and protection whereas plastic coatings are not environmentally friendly and completely isolate the earth walls from the environment as they need to be non-permeable to gases and moisture to prevent blistering. Natural clay renders such as kaolonite and laterite offer protection of the walls from harmful elements but easily wears and degrade however they are cheap and easy to repair or replace. These plasters are often reinforced with natural fibres and can be stabilised with synthetic or natural additives.

2.6 Construction of modern earth buildings

A modern approach is required when building with earth and/or natural materials as modern buildings are vastly different from traditional earth buildings. Some typical characteristics or differences between modern and traditional buildings which were derived from the literature (Houben and Guillaud, 2008; Minke, 2000, 2006 and 2007; Morton, 2008) are listed in Table 2.1. Such a modern building approach requires its own set of standards and techniques to ensure modern earth building materials are utilised to their full potential and to cater for the growing interest in earth building. All modern earth buildings need to be robust, eco-friendly, sustainable and healthy, changeable to suit the developing needs of people and desirable to remain attractive in order to compete with synthetic insulated modern builds. A durable structure must be able to withstand deterioration throughout its intended life without the need for undue maintenance.

A good building must preferably be a passive and breathable structure constructed using non-toxic materials and sustainable resources. A natural material such as earth for the walls of the building is ideal to satisfy these criteria and many building components made from natural materials such as hemp, wool, straw and wood-fibre exist to construct a passive building. A passive building is a well-insulated, air-tight building that is primarily heated in winter by solar gain and the heat from people and electrical equipment indoors from which energy loss is minimised. Any further heating required is supplied by an extremely small source. Shading and correct window orientation in the summer limits the need for artificial cooling. An energy recovery ventilator provides a constant, balanced fresh air supply to ensure a comfortable and healthy indoor air quality.

Table 2.1 Differences between modern and traditional buildings

Modern Buildings	Traditional Buildings
Airtight	Breathable
Inflexible	Flexible
Low maintenance	Repairable
Non-recyclable	Recyclable
Minimal labour	Labour intensive
Not produced locally	Produced locally

Owing to the many advantages of earth as a building material and the need to develop low energy, sustainable, eco-friendly buildings there has been a growing interest in earth building. Modern architecture has incorporated earth as a building material and traditional techniques such as rammed earth, adobe and the use of unfired clay masonry have been improved to suit modern styles and construction methods. A numerous number of organisations world-wide are conducting research into earth and earth construction. Such an empirical approach is increasing awareness and confidence to use earth in new builds and renovations and generate the funding necessary to establish earth as a desirable and robust material such as concrete, fired brick and steel.

Standards for earth building and earth building materials have been developed to ensure correct use of the materials and the construction of sound earth buildings such as the New Zealand Standards (NZS 4297:1998, NZS 4298:1998 and NZS 4299:1998) and the German regulation for building with earth in the EU (Lehmbau Regeln). Standards and regulations not only stipulate the specifications, construction techniques and tests required for earth building materials and earth construction but also ensure that earth is recognised as a modern building material and that it is not as variable as traditionally thought but can be standardised to compete with industrially manufactured building materials such as cement, concrete and fired brick.

Although advances in earth building are constantly being made and many modern designs are making use of earth it remains unsuitable for mainstream construction of domestic one and two storey dwellings. Construction using techniques such as rammed earth, adobe and compressed unfired clay blocks are substantially slower and the walls three times thicker (300 mm) than those made from concrete block or fired brick to achieve the compressive and flexural strengths required. The disadvantage of thick walls is the high material use and more importantly the significant decrease in floor space which is critical in modern construction in densely populated areas of the UK. A thin wall option where earth is used as an infill for timber frame is too slow to construct as time is as critical as space in modern construction.

A thin earth wall similar to concrete block or fired brick masonry that is quick to construct and consist of components that are reliable, robust and, fast and easy to manufacture is required. An ideal process to manufacture the masonry units is the industrial extrusion process used to produce fired clay bricks. Green or unfired clay brick or block units prior to firing once dried would suffice if they are manufactured to be of suitable compressive and flexural strength. Such thin unfired clay walls require good mortar bond strengths to avoid collapse under lateral loading.

A stable wall requires sufficient mortar bond strengths to achieve suitable flexural strengths and resist lateral loading. Stability of a wall depends on wall thickness and bond strength. A thick wall of the same height requires lower mortar bond strengths than a thin wall. For example, a vertical wall of 2.4 m high and 300 mm thick requires mortar bond strengths of 0.024 N/mm^2 to sustain a lateral load of 500 N/m^2. Reducing the thickness to 105 mm requires mortar bond strengths of 0.2 N/mm^2 to resist a similar lateral load (Heath et al, 2007).

Clay/sand earth mortars and conventional cement and lime mortars are not suitable for the construction of thin wall structures. Clay/sand mortars are weak and mortar bond strengths between unfired clay masonry units and earth and conventional mortars are weak substantially lower than the characteristic mortar bond strength of 0.2 N/mm^2 for the construction 100 mm thin walls used in modern builds (Lawrence et al, 2008 a, b). A bonding agent made from poly-vinyl acetate (PVA or commonly known as wood-glue) improved the bond strengths of earth and conventional mortars (Heath et al, 2007). Mortar bond strengths higher than the characteristic bond strength required were achieved on certain unfired clay masonry units with the cement and lime mortars when using PVA (Lawrence et al 2008).

Mortars developed from brick clays containing sodium lingo-sulphonate (a lignin based by-product from the paper industry commonly used as a binder and plasticizer) gave better but lower mortar bond strengths than the characteristic bond strengths required for thin walls (Lawrence et al, 2008). The PVA bonding agent used in conjunction with the lingo-sulphonate earth mortars developed gave mortar bond strengths higher than the characteristic bond strength required but only on certain unfired clay masonry units. A further disadvantage with the lingo-sulphonate mortar is the decrease in stability of the mortar with time as both mortar bond strengths and strengths of the mortar deteriorated with time. PVA is also synthetic and slows construction of the earth masonry.

A sodium silicate mortar available commercially which is used in the construction of furnaces gave good bond strengths with all the unfired clay masonry units tested (Lawrence et al, 2008). Owing to the high cost of the commercial mortar (five times the cost of lime mortar) an alternative solution was required. Mortars developed from brick clays to which sodium silicate powder was added (5 % by weight) gave good bond strengths. Strengths of the sodium silicate mortars were similar or higher than that of the unfired clay masonry units and the mortar bond strengths and the mortar strengths remained stable with time. Sodium silicate is not costly (£20/tonne) and has a low carbon footprint (60 kg CO_2/tonne).

A good earth building system for modern builds which is suitable for mainstream construction is therefore an unfired clay masonry system that is similar to the conventional concrete block or fired brick masonry systems currently used.

Unfired clay block or brick units can be mass produced using standard or modified brick clays and the clay-brick extrusion process where economy of scale will make the production cost-effective. Mortars giving good strengths and adequate bond strengths for thin wall construction can be developed from directly from the standard brick clays and sodium silicate.

A reliable, robust and consistent unfired clay masonry unit can be produced using the fired clay brick extrusion process. Variations in the chemical and physical properties of the unfired clay masonry units are minimal as strict control to ensure that the properties of the brick clays remains similar is necessary to produce unfired clay bricks which when fired give bricks of good quality that conform to standards stipulated for fired clay brick and fired clay brick construction in the UK. Standards and building regulations for the unfired clay masonry manufactured in this way could therefore be formulated as the variability associated with the sourcing of earth for traditional earth building techniques would therefore be eradicated. An unfired clay masonry system complete with standards for thin-wall modern builds and mainstream construction is therefore possible. Such a sustainable system would gain recognition and confidence allowing it to compete with the conventional concrete and fired-brick systems that meets the needs of the present but compromises the ability of future generations to meet their own needs.

2.7 Advantages of soil in construction

Although earth building materials have significant disadvantages when compared to industrial building materials such as variability, low strength and low water resistance and, for example, the rapid decrease in strength of unfired clay masonry units with the increase in moisture content (Heath et al, 2009 a, b) there are many advantages which favour their use in modern construction such as:

- control of indoor climate to provide comfortable and healthy building environments
- good sustainability and low environmental impact

2.7.1 Control of indoor climate

The control of the indoor climate in buildings particularly in domestic dwellings is essential to ensure the building remains comfortable for the inhabitants. Modern buildings are heated and cooled artificially to ensure a comfortable indoor climate. As a result modern buildings have high operational energies and therefore need to be insulated to minimise the energy usage during the buildings service life. Such well-insulated buildings are generally poorly insulated and create an unhealthy living environment, which lead to colds and other respiratory diseases. Constructing the building with earth or using earth inside the building to construct the interior walls for example, will assist in creating a healthy breathable building and improve on the indoor living conditions such as air humidity, temperature, and the absorption of odours, electromagnetic radiation and microwaves. Good control of the indoor climate and the absorption of odours demand less ventilation.

Control of air humidity

Air humidity of an earth building is balanced due to the ability of earth in particular unfired clay (Rode and Grau, 2008) to absorb and release water vapour from and into the air more efficiently than all other building materials. Absorption of water vapour from the air and the release of water vapour into the air are due to the hygroscopic nature of the clay. Absorption and the release of water vapour is diffusion controlled and depends on the relative humidity (i.e. moisture concentration in the air) and moisture content in the unfired clay wall. Water is absorbed up to the equilibrium moisture content (i.e. maximum moisture a dry material can absorb) of the unfired clay wall in moist conditions.

The hygroscopic nature of clay is not responsible for the movement of moisture inside or through the unfired clay wall. Clay particles attract and hold water molecules but water movement results from permeability and capillarity of the clay material. Permeability is the capacity of the water vapour to pass through the clay material and capillarity is the ability to mop-up or wick away water in its liquid form.

Measurements done in an earth house over a period of 8 years showed that indoor relative humidity remained fairly constant and only varied from between 50 % to 60 % throughout each year (Minke, 2000). Unfired clay brick walls were shown to absorb moisture when the relative humidity rose above 50 % and release moisture when the relative humidity dropped below 50 % thereby controlling the indoor humidity (Minke, 2007). Adobes conditioned in a climatic chamber at 95 % relative humidity for 6 months did not get wet or lose their stability and their equilibrium moisture content of approximately 5 % to 7 % by weight was not exceeded (Minke, 2000).

At an indoor relative humidity of 50 % an unfired clay brick wall absorbed ten times more moisture in 48 hours than a fired clay brick wall (Minke, 2007). On raising the relative humidity to 80 % unfired clay brick walls absorbed thirty to fifty times more moisture than fired clay brick walls in 48 hours (Minke, 2000 and 2007). For example, a 30 m^2 of unfired clay wall absorbed 9 ℓ of water in 48 hours compared to 0.9 ℓ for a fired clay brick wall of similar area.

A further investigation to determine water vapour absorption capacity showed that 300 g/m^2 of water was absorbed into the outer 15 cm of an unfired clay brick wall when the relative humidity increased from 50 % to 80 % compared to 100 g/m^2 for timber and 30 g/m^2 for a fired clay brick wall (Morton, 2008). Absorption due to the hygroscopic nature of the unfired clay was found to first occur within the outer surfaces of the unfired clay walls. Water vapour was only absorbed into the outer 2 cm of an unfired clay wall within the first 24 hours and then into the outer 4 cm over the next 72 hours when relative humidity was increased from 50 % to 80 % (Minke, 2000).

Absorption of water vapour not only controls the indoor humidity but also clears the indoor air, for example, after showers and cooking, and prevents condensation on cold surfaces. Control of the indoor air humidity is however the most important advantage of the unfired clay building materials. Air humidity inside domestic dwellings significantly influences health and comfort of inhabitants. An indoor relative humidity of between 40 % and 70 % is ideal and maximises comfort and minimises conditions associated with major health conditions. Such an indoor climate is easily maintained with the use of interior unfired clay walls which is a major step in creating a healthy modern building.

A relative humidity lower than 40 % over prolonged periods dries out the mucous membrane which leads to a decrease in resistance to colds and other related diseases (Minke, 2000). The mucous membrane is responsible for the absorption and transportation of the fine dust particles that carry bacteria and viruses out to the mouth before they enter the lungs. An increase in relative humidity of up to 70 % significantly improves conditions in a building such as:

- reduces fine dust content of the indoor air
- activates the protection mechanisms of the skin against microbes
- decreases life of bacteria and viruses
- creates a comfortable indoor climate
- minimises odour
- eliminates static charge on the surface of objects

A relative humidity above 70 % is unpleasant and increases growth of moulds and fungi which lead to allergies and is linked to the increase in asthma in the UK, for example, 18,4 % in Scotland and 15,3 % in England compared to 6,9 % in Germany and 2,3 % in Switzerland (Howieson, 2005). Allergens relating to the house dust mite provide mechanisms relating to the cause of asthma and act as an irritant which triggers or exacerbates the symptoms of asthma. House dust mites proliferate above a relative humidity of 70 % as their metabolism depends on the absorption of water from the atmosphere. The ideal conditions for growth is at a temperature of 25 °C and a relative humidity of 80 % (Howieson, 2005). Water is released from the dust mite into the atmosphere when the relative humidity falls below 73 % (the critical equilibrium humidity at 25 °C) and dehydration occurs decreasing the life span of the house dust mite (i.e. life span at 40 % to 50 % relative humidity is between 8 days to 11 days).

Storage and release of heat

Earth as with concrete and fired clay brick possesses good thermo-physical properties (i.e. the ability of a material to absorb, store and release heat). Specific heat capacity of earth building materials (800 – 1000 J/kg.K) are similar to that of concrete (880 J/kg.K) and fired brick (840 J/kg.K) (Morton, 2008). Volumetric heat capacities or thermal mass of earth building materials such as compressed earth blocks (1740 kJ/m^3.K), rammed earth (1673 kJ/m^3.K) and adobe (1300 kJ/m^3.K) is lower than that of concrete (2060 kJ/m^3.K), higher or similar to that of fired brick (1360 kJ/m^3.K) and substantially higher than that of aerated concrete (550 kJ/m^3.K).

Such high thermal mass materials absorb energy slowly and hold the energy for longer times. A delay and reduction in heat transfer through the building component results limiting fluctuations and moderating indoor air temperatures. During the summer months the wall cools naturally during the evening and absorbs heat slowly during the day. As a result heat penetration from the outside is prevented and the house remains cool when the peak outdoor afternoon temperatures are reached. During the winter months the heat absorbed from the sun, domestic activity and mechanical heating devices is stored and released to assist in keeping the house warm during the off-peak evening period. A sound passive design technique is required to ensure effective use of these high thermal mass elements. Solar gain must be maximised during the winter months and walls must be shaded during the summer months. On winter nights heat loss and absorption of heat generated inside the building must be minimised.

2.7.2 Sustainability

Construction is the key factor in the control of a buildings operational energy throughout its service life. Operational energy needs to be minimised to ensure the building is energy efficient and sustainable. A building albeit constructed of synthetic or natural materials needs proper insulation to minimise the energy usage during service. A poorly insulated building constructed with natural materials will use more resources than a building with good insulation constructed with synthetic materials.

Sustainable buildings demand the use of renewable resources (natural fibres, textiles and food products), abundant resources (clay, sand and chalk), recyclable materials and reusable materials (i.e. promoting an indefinite use of materials). Sustainability strives towards achieving green buildings:
- energy efficient (i.e. low operational energy, low carbon dioxide emissions, low embodied energy and embodied carbon)
- passive (i.e. absorb energy from the sun, ventilate naturally, naturally insulate and have good thermal mass)
- harmonise with nature
- limit disruption of eco-system
- reduce water usage
- minimise waste
- use materials and methods to minimise energy and resource depletion
- avoid materials and methods that cause pollution
- avoid toxic materials

Non-sustainable buildings make use of high energy materials (i.e. high embodied energy and embodied carbon materials), materials in limited supply, materials that cannot be replaced, non-recyclable or non-renewable materials and materials requiring large amounts of energy to recycle. Modern construction tends to demand the use of synthetic materials and creates considerable waste (i.e. materials stripped after use are thrown away rather than recycled or repaired which proves hazardous to the environment).

Although the use of high-energy synthetic materials drastically reduces the operational energy of a building the total amount of energy used and pollution generated during a buildings entire life cycle (i.e. from cradle - extraction of materials to grave – disposal of materials) in many cases does not outweigh the advantages modern buildings offer during their limited lifespan. A detailed life cycle assessment is required to assess the impact of the building on the environment during its life cycle to validate its advantages. A life cycle assessment evaluates the burdens a product, process or activity has on the environment by identifying and quantifying the energy and materials used and the waste released into the environment and assesses their impact on the environment and identifies opportunities to affect environmental improvements by considering:

- extraction and processing of raw materials
- manufacturing processes
- transportation and distribution
- maintenance
- use and reuse
- recycling
- final disposal

Sustainability in buildings can only be achieved with a multi-disciplinary approach which considers energy savings, improved use of materials, reuse and recycling of materials and pollution (emission control, wastage and disposal). An alternative building material to concrete and fired clay brick such as unfired clay blocks will assist in achieving these goals as they require less energy to produce thereby lowering carbon emissions, are reusable and recyclable, reduce wastage and have a low impact on the environment on disposal.

Concrete building products and fired clay bricks are of a significantly higher embodied energy and embodied carbon than unfired clay bricks (Table 2.2). A saving in the embodied energy is becoming more significant owing to the substantial reduction in the operational energy achieved in modern buildings. For example, a three-bedroom house of 92 m^2 in which earth masonry forms the internal partitions and inner face of the external walls a saving of about 24.9 MWh of energy and 7 tonnes of CO_2 over fired clay bricks and 14.5 MWh of energy and 4 tonnes of CO_2 over lightweight concrete blocks is achieved (Heath et al, 2007).

Table 2.2 Embodied energy and embodied carbon of building materials (Hammond and Jones, 2006)

Material	**Embodied Energy** (MJ/kg)	**Embodied Carbon** ($kgCO_2/kg$)
Concrete block	0.67	0.073
Aerated block	3.50	0.30
Unfired clay	0.45	0.023
Cement mortar (1:3)	1.33	0.208
Fired clay	3.00	0.24

Reducing the use of fired clay brick alone saves a significant amount of energy per year. The UK brick manufacturing industry consumes 5.4 TWh of energy per year (BDA, 2002). Assuming that 85 % of the energy is used in firing then replacing 1 % of the fired clay brick with unfired clay brick saves energy sufficient to power 2000 UK homes per year (BGS, 2005).

A number of drastic measures are required in the building industry to help achieve the target of a 60 % reduction in carbon emissions in the UK by 2050. Construction consumes 40 % of materials in the UK and generates 40 % to 50 % of the green house gases (Asif et al, 2007). Construction and demolition waste figures for the UK in 2005 were 89.6 million tonnes in total (Morton, 2008). Construction and demolition of buildings accounts for 72 % of landfill waste and 13 % of building products delivered to construction sites are sent directly to landfill. A total of 2.7 million bricks per year are produced in the UK which equates to 8 million tonnes of raw materials, 4.06 billion kWh of natural gas and 1 million tonnes of CO_2 emissions per year (Heath et al, 2007). Construction must therefore aim to use low embodied energy and embodied carbon products, reuse or recycle to avoid waste and minimise disposal to landfill.

2.8 Masonry material testing

Standard tests are only available for industrialised building materials in the UK. A number of specifications and standard procedures exist for construction and testing of concrete block and fired-clay brick masonry. Assessing the suitability of unfired clay masonry for mainstream construction in the UK requires testing using these procedures where possible to give confidence in their properties. The standard testing procedures that are not representative of earth structures and to severe for the testing of the unfired clay masonry need to be modified to suit the intended applications of the unfired clay masonry. Suitability of the unfired clay masonry for the construction of thin non-load bearing inner walls can then be determined by comparing to the specifications stated in Eurocode 6 and the UK national annex (NA) to Eurocode 6 for the design of masonry structures (refer to BS EN 1996 and BS (NA) EN 1996).

Eurocode 6 applies to the design of buildings in un-reinforced and reinforced masonry and deals with the requirements for resistance, durability and serviceability of the structures, quality of construction materials and products required and standard of workmanship required onsite to comply with the design requirements.

1. General rules for reinforced and un-reinforced masonry structures (BS EN 1996-1.1:2005 and BS EN (NA) 1996-1.1:2005) gives the requirements for design, materials (i.e. masonry units and mortar), durability, structural analysis, ultimate limit states, service limit state, detailing and execution.
2. Design considerations, selection of materials and execution of masonry (BS EN 1996-2:2006 and BS N (NA) 1996-2:2006) gives basic rules for the selection of materials and execution of masonry to comply with Eurocode 6 (selection of masonry materials, factors affecting the performance and durability of masonry, resistance of buildings to moisture penetration, storage, preparation and use of materials on site, execution of masonry, masonry protection during execution).
3. Simplified calculation methods for un-reinforced masonry structures (BS EN 1996-3:2006 and BS N (NA) 1996-3:2006) gives calculation methods to facilitate the design of un-reinforced masonry walls (walls subjected to vertical loading and wind loading, walls subjected to concentrated loads, shear walls, basement walls subjected to lateral earth pressure and vertical loads, walls subjected to lateral loads but not subjected to vertical loads).

A comprehensive list of the relevant standard test procedures and specifications is given in Eurocode 6. Characteristics and performance requirements for masonry units manufactured from clay and concrete for use in load bearing or non-load bearing structures are specified in BS EN 771:2003 – Specification for masonry units. The requirements for masonry mortars for load bearing and non-load bearing structures are specified in BS EN 1998:2003 – Specification for mortar for masonry. Standard test procedures to assess if the masonry units conform to these characteristics and performance requirements are essential for construction but most are beyond the scope of this investigation. Only a few standard test procedures mainly to check suitability of the unfired clay masonry units for construction of non-load bearing walls were required for this investigation namely determination of:

- dimensions and tolerances of masonry units (BS EN 772-16:2000)
- density of masonry units (BS EN 772-13:2000)
- compressive strength of masonry units (BS EN 772-1:2000) and masonry (BS EN 1052-1:1999)
- flexural strength of masonry (BS EN 1052-2:1999)
- initial shear strength of masonry (BS EN 1052-3:2000)
- mortar bond strength (BS EN 1052-5:2002)

Other British standard test procedures of interest in this investigation and required for future testing of unfired clay masonry were generally too severe. Suitable tests or similar test procedures need to be developed to determine properties such as water absorption and movement, durability, porosity, permeability, heat storage and release, humidity control and equilibrium moisture content, hardness and impact resistance, erosion, wear and abrasion, and accelerated and natural ageing. Standards such as the New Zealand Standards (NZS 4297:1998, NZS 4298:1998 and NZS 4299:1998) give good specifications and standard test procedures similar to those in Eurocode 6 but specifically for earth materials and structures. Such standards are better suited for unfired clay masonry intended for mainstream construction. A number of rudimentary test procedures for earth materials found in traditional earth building publications are also useful (Houben and Guillaud, 2008; Minke 2000 and 2006; Walker, 2005).

2.9 Clay brick manufacture for mainstream construction

One of the oldest building materials known to man is mud brick (discoveries dating to before 7500 BC), which were shaped by hand (Houben and Guillaud, 2008). Owing to the reasons of speed and economy mud bricks became more popular than the use of stone and the mechanisation for the manufacture of bricks started to evolve. Modern brick manufacture uses one of three methods namely:

1. Stiff-mud or extrusion process – ground clay at 10 % to 15 % water content is mixed, de-aired in a vacuum chamber and extruded to form a column of clay which is cut into brick sized units
2. Soft-mud or moulded process – ground clay at 20 % to 30 % water content is mixed and formed into bricks in moulds by machine or by hand
3. Dry-press process – ground clay of very low plasticity is mixed with a minimal amount of water (less than 10 %) and pressed into steel moulds (compression pressure ranges from 3.4 N/mm^2 to 10.3 N/mm^2) (BIA, 2006)

Extrusion is the most common and suitable process for the manufacture of fired clay bricks for mainstream construction. For example, approximately 90 % of the fired clay bricks in the USA are produced in this way (BIA, 2006). Clay for the extrusion of bricks or brick clay is a mixture of clay and shale (i.e. clays that have hardened due to high pressures) in other words sedimentary mudstones of different geological ages and compositions that vary from soft plastic clays to hard mudstones. Although commonly referred to as brick clay, clay is not the correct term to describe these soils. Clay is the binder like cement in concrete that binds together the silt, sand and gravel grains present in the soil. A more precise terminology is loam which is a soil containing approximately 20 % clay, 40 % silt and 40 % sand.

Chemical properties, mineralogical composition and physical properties are critical in determining the suitability of the brick clay. Sedimentary clays consist mainly of clay minerals and quartz. Sufficient clay minerals are required to form a semi-solid paste of good plasticity for moulding so that the *"green bricks"* extruded prior to firing can retain their shape. Kaolinite and illite are the predominant clay minerals in good quality brick clays (Ibstock, 2005).

The brick manufacturing process consists of five main phases:

1. Mining and storage of raw materials
2. Preparation of the raw materials (grinding, screening and mixing)
3. Forming of the bricks (extrusion, wire cutting and coating or glazing)
4. Drying, firing and cooling
5. Storage and shipping

2.9.1 Mining and storage of raw materials

Clays typical of that used for the extrusion of fired clay bricks are usually mined from quarries once or twice a year during periods of good weather using heavy machinery to build up large stockpiles, which ensures a continuous supply of clay close to the factory throughout the year (Figure 2.1). Stockpiles are layered to eliminate localised variations in the clay strata (i.e. to homogenize different raw material grades within quarry). Clays from different parts of the quarry are tested in the laboratory to determine the characteristics of the layers and the desired mixture to produce a specific brick. Souring is the process whereby stockpiles are allowed to weather to increase the plasticity of the clay.

Figure 2.1 Typical mining and stockpiling processes for the clay used in the extrusion of fired clay bricks (Ibstock, 2005)

2.9.2 Raw material preparation

Raw materials from the stockpile are transported to storage areas. A primary crusher breaks up large chunks of clay or shale to a manageable size. Conveyors transport the crushed clay to grinders (pan mills or 'Muller Wheels') which pulverize the material to a fine consistency (Figure 2.2). A vibrating screen allows the fine material (less than 2 mm particle size) to pass through to storage silos or piles and the coarse material returns to the grinders (Figure 2.2).

Figure 2.2 Raw material preparation (a) pan mills (b) screening (c) storage (d) mixing (Glen-Gery Brickwork Design Guide, 2010)

Water (10 % to 15 %) is mixed into the clay using a pug mill (i.e. a mixing chamber with one or two revolving shafts with blade extensions) to produce a clay with the desired consistency for forming.

2.9.3 Extrusion of green bricks

After the pug mill the tempered clay passes through a de-airing or vacuum chamber (375 mm to 725 mm of mercury) to increase workability and plasticity of the clay and give good strength of green bricks after forming. Clay is then extruded through a die at a high pressure to produce a dense rigid column of clay (Figure 2.3). An automatic wire cutter slices through the clay column to create the individual green bricks (Figure 2.3). The green bricks are palletised and then sent to the dryer.

2.9.4 Drying and firing

Green bricks are dried in an oven using exhaust heat from the kilns. Ovens are kept at temperatures of from about 80 °C to 120 °C and bricks are dried from 18 hours up to 40 hours depending on the nature of the clay, and size and shape of the green bricks. Oven-drying prior to firing is essential. All moisture or as much as possible must be removed to prevent the bricks from exploding in the kiln. Bricks must dry out evenly from the inside outwards. If the outer skin brick dries first the moisture from inside will be forced out in the kiln and cause cracking. A very humid atmosphere is maintained in the dryers to keep the exterior of the brick moist to allow proper drying. Heat and humidity are carefully regulated to obtain the desired drying rate and direction, and avoid cracking. The oven-dried bricks are strong enough to be stacked onto kiln cars ready to be fired.

Figure 2.3 Clay brick extrusion (a) die fitted to extruder (b) perforate die plate (c) extruded column of clay (d) wire cut perforated unfired or green clay blocks

The oven-dried bricks are fired in tunnel kilns fuelled by natural gas. Firing takes from 2 days to 4 days depending on the clay properties, size and shape of bricks, and appearance and properties required. A tunnel kiln is constructed to perform various firing and cooling cycles. A kiln car moves through the tunnel kiln slowly passing through the different firing cycles and finally a cooling cycle.

Oven-dried bricks are first preheated at 204 °C to ensure complete evaporation of the free water. Bricks then pass through a dehydration cycle where the temperatures range from 150 °C to 980 °C followed by an oxidation cycle with temperatures ranging from 540 °C to 980 °C. After oxidation the bricks are vitrified at temperatures ranging from 900°C to 1400°C. Vitrification of the clay is a physical change where the clay particles and impurities in the brick are fused together to produce a hard, durable and weather resistant product. After vitrification the brick may be subject to a cooler flashing or reduction cycle to give a lighter colour than that obtained in the virtrification cycle. After the firing cycles a cooling cycle of approximately 10 hours ensures that the bricks are cooled at the correct rate to prevent cracking and give the desired colours. Once cooled the fired clay bricks are palletised and stored ready for shipping.

2.10 Conclusion

It is evident from the literature that earth is fundamentally perceived as a traditional building material and is rarely considered for modern builds. This is due to the conception that earth is a low strength material and unable to resist the elements particularly in wet climates. Earth will continue to endure this stigma until it becomes recognised as a building material with empirical specifications and standard test procedures to suit the requirements of modern mainstream construction. It is within this domain that the research documented here is not only necessary but essential to the recognition of earth in modern construction.

Extruded unfired clay masonry units are probably the most suited earth material for mainstream construction. They are manufactured as quickly as concrete blocks and fired clay bricks, are as easy to construct with and are suitable for the construction of thin-walls. This research to develop an unfired clay masonry system suitable for the mainstream construction of thin non-load bearing walls would give earth recognition and if successful promote further research into unfired clay masonry and earth construction and eventually lead to the formulation of standards similar to that for concrete block and fired clay brick masonry. The health and environmental benefits of unfired clay masonry will ensure it competes with conventional masonry used in the construction of inner walls.

The literature review serves as a strong foundation from which to conduct the research. A good understanding in soil as a construction material such as soil classification, properties, identification and standard test procedures was obtained. A good background study in traditional earth building was done and the use of earth in modern builds and mainstream construction was identified. The differences in modern buildings and traditional buildings and the importance of constructing sustainable modern buildings were defined. The limitations and the benefits of using earth were documented and discussed in particular health and environmental benefits. Specifications and standards of relevance to earth building and masonry construction were discussed. The brick manufacturing process was described to assist with references made within this document.

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CHAPTER 3

DEVELOPMENT OF UNFIRED CLAY MASONRY UNITS

3.1 Introduction

Extrusion is the most practical method to manufacture unfired clay masonry units for mainstream construction. A large number of units (in excess of 10000 per hour) consistent in shape, size and properties can be produced in a single plant. The units are dense, of low water content (10 % - 15 %) and can easily be perforated. After production the unfired clay or green units can be dried in ovens (approximately 100 °C) heated by waste heat from the kilns used to fire conventional bricks. Alternatively the green units can be left to air-dry.

The aim is to develop an unfired clay block of dimensions similar to that of standard concrete blocks (440 mm × 215 mm × 100 mm) used in mainstream construction. This is to limit the amount of mortar needed for construction and to be compatible with the construction of standard 100 mm thick walls. A clay block of these dimensions requires perforations to reduce weight and modifications such as the addition of plant fibres to improve on toughness to reduce breakages during handling and transportation.

This chapter documents and discusses testing done on materials intended for use in the development of prototype unfired clay masonry units to determine:
- characteristics of extruded unfired clay units
- properties of standard brick clays
- properties of standard extruded unfired clay brick units
- properties of brick clay specimens containing plant fibres

The scope of the tests was to determine:
- particle size distribution of brick clays
- liquid limit, plastic limit and plastic index of brick clays
- linear shrinkage of brick clays
- dimensions and density of masonry units
- compressive and flexural strength of masonry units
- shrinkage and swelling of masonry units

3.2 Characteristics of extruded unfired clay units

A preliminary investigation was done on extruded unfired clay blocks (referred to as Units 1), which were specifically extruded for a previous research project, to gain an understanding into the nature of the soil and to ascertain the suitability of the extruded units for the construction of non-load bearing inner walls. These blocks were supplied from a typical commercial extrusion plant. The dimensions of the blocks with respect to width, thickness and height were 370 mm × 105 mm × 210 mm. Tests were conducted to determine:
- properties of soil used in the extrusion of bricks
- density and compressive strength of the extruded unfired clay units
- effect of extrusion direction on compressive strength
- suitable test specimen preparation techniques (capping versus grinding)
- relationship of compressive strength to moisture content

- influence of shape and size of test specimens on compressive strength
- influence of perforations on compressive strength

3.2.1 Soil analysis

A representative sample of the brick clay (referred to as Soil 1) was analysed as documented in BS 1377-2:1990. Soil 1 is described as very clayey silt and fine to coarse sand with traces of fine gravel. It is therefore not clay, which is defined as soil containing more than 35 % clay sized particles (i.e. particles less than 2 μm in size). The complete analysis data of Soil 1 including grading and plasticity charts is documented in section 3.3 below, which discusses soils typical of that used for the extrusion of green unfired clay brick units intended for the manufacture of fired clay brick units.

Soil 1 contained 4.2 % gravel, 36.0 % sand, 34.6 % silt and 25.3 % clay (refer to section 3.3 Table 3.4 and Figure 3.4). Soil 1 has a linear shrinkage of 9.6 % and plastic index of 19 % (liquid limit of 37 % and plastic limit of 18 %), that is it is a soil of low plasticity (refer to section 3.3 Table 3.4 and Figure 3.5).

3.2.2 Determination of density and compressive strength

Density of the brick units were determined using the gross density method documented in BS EN 772-13:2000 on cubes (100 mm × 100 mm × 100 mm) cut from the unfired clay units. Cubes were oven dried at 105 °C to attain a constant mass (± 24 hours). Once dried their dimensions were determined to calculate volume and density.

Compressive strength was determined using the method suggested in the British Standard (BS EN 772-1:2000) for testing of fired clay brick units (Figure 3.1). Cubes (100 mm × 100 mm × 100 mm) were cut from the blocks and capped using dental plaster. A paste was made by mixing water and dental plaster. A layer of the dental plaster was then applied onto a smooth oiled surface into which the test specimen was inserted. The excess plaster was trimmed around the specimen edges to form a cap. After the plaster sets the specimen was delaminated and the opposite end was then capped in a similar manner to the first making sure the capped surfaces were parallel and the edge faces of the cube were at 90° to the capped surfaces.

Cubes were conditioned at ambient conditions (20 °C and 60 % - 65 % RH) for 28 days prior to testing. Compressive strengths when loading in the direction of extrusion of the cubes were determined. Dimensions and loads were recorded to three significant figures. Specimens were loaded at a rate of 50 N/s until failure. Moisture contents of the cubes were determined directly after compressive strength tests. A portion of the crushed cube was weighed and oven dried (105 °C) to a constant mass and the percentage moisture was calculated.

Density of the extruded unfired clay units was 2056 ± 6.4 kg/m^3 (average of six determinations). Compressive strength (average of six determinations) of the cubes at 2.25 % moisture contents was 3.37 ± 0.15 N/mm^2. Strengths of individual specimens were all above the minimum strength required for non-load bearing thin-wall construction (i.e. 2.50 N/mm^2 - BS EN 1996-1-1:2005) indicating that the brick clay and extrusion method was suitable for the manufacture of unfired clay units for mainstream construction.

Figure 3.1 Compressive strength test of cubic specimens (100 mm × 100 mm × 100 mm) cut from Units 1 showing dental plaster cap

3.2.3 Effect of extrusion direction on compressive strength

A series of cubes (100 mm × 100 mm × 100 mm) and prisms (100 mm × 100 mm × 200 mm) were cut from the unfired clay blocks and capped to compare compressive strength when loading in the direction of extrusion to that when loading at right angles to the direction of extrusion. Specimens were conditioned for 28 days at ambient conditions prior to determining compressive strengths.

Applying the load in the direction of extrusion gave similar compressive strengths (average of six determinations) at 2.50 % moisture contents for both the cubic (3.07 ± 0.13 N/mm^2) and prism (2.99 ± 0.28 N/mm^2) shaped specimens to those when loading the cubes and prisms at right angles to the direction of extrusion (3.00 ± 0.23 N/mm^2 and 2.98 ± 0.10 N/mm^2 respectively).

An analysis of variance (ANOVA) of the data confirms that statistically there was no significant difference between the mean compressive strengths calculated. This indicates that the orientation of the flat clay particles in the direction of extrusion has negligible effect on compressive strength of the extruded brick clay material.

3.2.4 Assessing specimen preparation techniques

A series of cubes cut from the blocks were capped to assess the effect water absorption into specimens has on compressive strength and the time required for the specimens to stabilise (i.e. with regard to moisture content and compressive strength) under ambient conditions. Compressive strength was measured in the direction of extrusion.

Compressive strength directly after capping was significantly lower than that after conditioning for 28 days at ambient conditions (Table 3.1). Specimens required a drying time of approximately 21 days at ambient conditions (20 °C and 60 % - 65 % RH) to achieve stable moisture contents and strengths. This indicated that:

- moisture content significantly influenced compressive strength
- moisture absorption due to capping reduced the compressive strength
- compressive strength decreased with an increase in moisture content
- conditioning for 28 days at ambient conditions was sufficient to stabilise capped specimens

Table 3.1 Compressive strength and moisture content with time of cubic specimens capped with dental plaster and conditioned at ambient conditions (20 °C and 60 – 65 % RH)

Drying times (days)	**Strength** (N/mm^2)	**Moisture** (%)
0	2.65 ± 0.34	3.03 ± 0.04
3	3.05 ± 0.08	2.53 ± 0.05
5	3.24 ± 0.18	2.25 ± 0.04
14	3.25 ± 0.17	2.04 ± 0.05
21	3.41 ± 0.12	1.98 ± 0.04
28	3.41 ± 0.19	1.97 ± 0.03

A series of cubes were cut to assess grinding as opposed to capping. Six specimens were capped and the two opposite sides of a further six specimens were ground smooth and parallel to one another. Grinding was done dry using a coarse grit sand paper and a belt grinder. Specimens were conditioned under ambient conditions for 28 days prior to measuring compressive strength. Compressive strengths were determined in the direction of extrusion.

Compressive strengths (average of six determinations) at 2.50 % moisture contents for the ground specimens (2.90 ± 0.25 N/mm^2) and capped specimens (3.07 ± 0.13 N/mm^2) were similar. Statistically (ANOVA) no significant differences between the mean compressive strength values calculated exist. This indicates that both methods were suitable in determining the compressive strength of unfired clay units.

Grinding of the specimens was however considered impractical. Although the grinding eliminates water absorption the specimens for compressive strength tests required conditioning for at least 28 days at ambient conditions to stabilise and this allows sufficient time for capped specimens to dry-out. Obtaining smooth parallel surfaces was time consuming and the sand paper required regular replacement

3.2.5 Compressive strength versus moisture content

A series of cubes capped with dental plaster were sprayed with a fine mist of water under ambient conditions to attain specimens at various moisture contents. Specimens were wrapped in cling film and inserted into a polyethylene bag which was sealed to restrict water evaporation. Specimens were left to normalise for 28 days at ambient conditions. Compressive strengths (in the direction of extrusion) and moisture contents of the specimens were determined and their relationship observed.

Compressive strength initially decreased sharply with an increase in the moisture content (Figure 3.2), as noted in Heath et al (2009 a, b). This was due to the increase in water content which causes a decrease in cohesion between the clay particles. Clay particles attract the water molecules causing separation between these plate-like clay particles (i.e. swelling of the brick clay) and easier slippage eventually leading to softening.

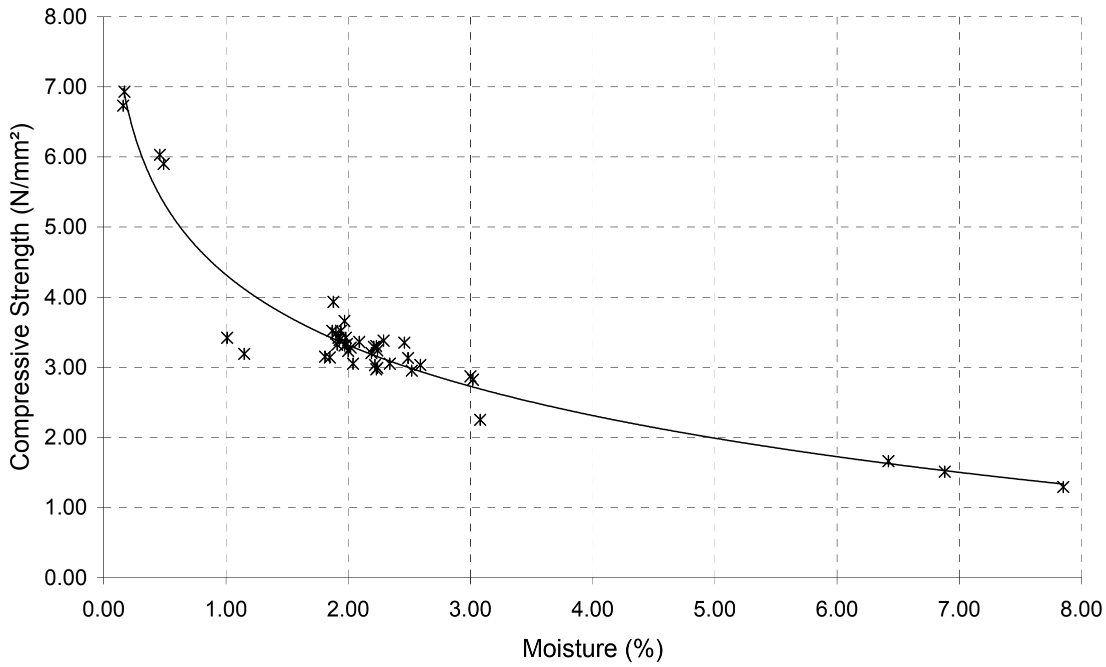

Figure 3.2 Compressive strength versus moisture content of cubic specimens cut from unfired clay blocks – Unit 1

3.2.6 Influence of shape and size of specimens on compressive strength

Specimens of various shapes and sizes were cut from the unfired clay blocks (refer to Table 3.2). Specimens were capped and conditioned under ambient conditions for 28 days. Compressive strengths were determined in the direction of extrusion.

Table 3.2 Compressive strengths of regular and irregular shaped prisms cut from unfired clay blocks referred to as Unit 1 (Stdev – standard deviation and Var – variance)

Dimensions (mm)	**Strength** (N/mm^2) *As measured*	*BS Normalised*	**Stdev**	**Var**
100 ×100 × 100	3.07	3.07	0.13	0.02
109 ×105 × 65	3.18	2.70	0.06	0.00
220 ×105 × 65	2.94	2.50	0.11	0.01
105 ×57 × 212	3.04	4.41	0.24	0.06
100 ×100 × 200	2.99	4.03	0.28	0.08

Compressive strengths (average of six determinations) at 2.50 % moisture contents of the irregular prism and regular brick sized specimens were similar to standard cubic specimens (Table 3.2). The shape and size of the test specimens did not significantly influence compressive strengths. Statistically (ANOVA) there was no significant difference between the mean compressive strength values calculated.

A geometric factor to correct for deviation in size and shape from the standard cubic specimens is suggested by the British Standard (BS EN 772-1:2000). Applying the factor significantly underestimates or overestimates the compressive strength of the material (Table 3.2). The standard applies to high strength materials such as fired clay and concrete and this testing indicates it may not be applicable for low strength materials. As a result, unit compressive strengths throughout this document are not normalised for dimensions and the measured values are reported.

3.2.7 Influence of perforations on compressive strength

A series of block sized specimens (180 mm × 105 mm × 212 mm) were cut from the unfired clay blocks (Table 3.3). Solid and perforated blocks were tested. Blocks were perforated by either drilling 8 × 25 mm diameter holes or coring 2 × 50 mm diameter holes through the blocks (Figure 3.3a). Solid and perforated blocks were capped and conditioned under ambient conditions for 28 days. Compressive strengths were determined when loading in the direction of the perforations and at right angles to the perforations.

Table 3.3 Compressive strength of solid and perforated block specimens at a moisture content of 3.00 % (Stdev – standard deviation and Var – variance)

Specimens (180 mm × 105 mm × 212 mm)	**Strength** (N/mm^2) *Gross*	*Net*	**Stdev**	**Var**
Solid	2.83	2.83	0.24	0.06
2 × 50 mm perforations (0° to load)	1.97	2.49	0.11	0.01
2 × 50 mm perforations (90° to load)	1.30	2.48	0.05	0.00
8 × 25 mm perforations (0° to load)	2.27	2.86	0.14	0.02

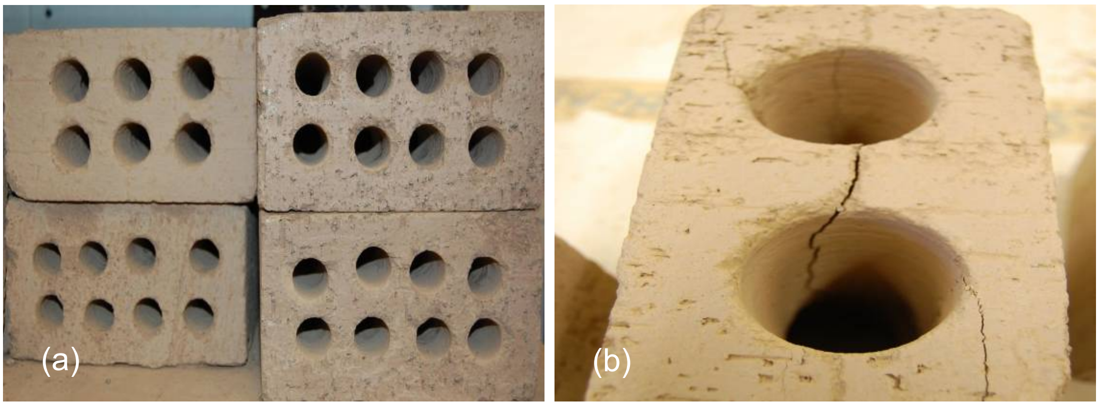

Figure 3.3 Specimens (180 mm × 105 mm × 212 mm) cut from Unit 1 blocks showing (a) drilled perforations (b) crack appearing between the 2 × 50 mm diameter cored-perforations

Gross compressive strengths (i.e. strength without compensating for the area of perforations) at 3.00 % moisture contents of the specimens with perforations were lower than those of the specimens without perforations. Strength of specimens with 2 × 50 mm diameter perforations was substantially lower than that of specimens with 8 × 25 mm diameter perforations (Table 3.3). Strength with perforations at 90° to the direction of loading was significantly lower than that with the perforations in the load direction. Cracks developed through the web area between the 2 × 50 mm diameter perforations at 90° to the direction of loading at a load of 0.63 N/mm^2 (Figure 3.3b). Net compressive strength, which compensates for the reduction of area due to the perforations in the load direction for the 50 mm diameter perforated specimens, was lower than that of the solid and 8 × 25 mm perforated specimens.

A statistical analysis of the data (ANOVA) was not appropriate as the mean compressive strengths calculated for the solid and 50 mm diameter perforated specimens tested were only based on two determinations. The tests were purely to gauge the effect of the perforations on the strength of the unfired clay masonry units to assess the possible formats of extruded unfired clay blocks, namely whether blocks with perforations running in a horizontal direction were suitable for the construction of thin non-load bearing walls.

3.2.8 Concluding remarks and discussion

Soil analysis

Soil 1 did not have characteristics typical to that of clay which by definition contains more than 35 % particles less than 2 μm in size. Soil 1 is more accurately classified as a clayey soil with low to intermediate plasticity. Such a soil is suitable for the manufacture of fired clay bricks (BIA, 2006 and Brick and Tile Industry, 2012). The plasticity is sufficient to extruded stiff and strong green unfired clay brick units, which resist deformation during handling and drying, giving brick units of good tolerances. The amount of clay minimises shrinkage, which could lead to cracks, during the drying and firing of the green brick units and is also adequate for the vitrification during the firing of the green bricks.

Sample preparation and effects of dimensions and extrusion direction

Capping was the most convenient method to determine the compressive strength of the extruded unfired clay units. Grinding was time consuming and labour intensive and not needed as the conditioning time required for the test specimens was sufficient to stabilise capped specimens with respect to moisture content and compressive strength. Strengths could be determined in the direction of extrusion or at 90 °C to the extrusion direction. Shape and size of the test specimens did not affect compressive strength measurements and geometric factors as stated in the British Standard were not needed to normalise the measurements, for example, when testing standard brick sized units (220 mm × 100 mm × 65 mm).

Compressive strength and moisture content

Compressive strengths determined indicate that the extruded unfired clay blocks were suitable for the construction of non-load bearing inner walls. Strengths were similar to that of low strength aerated concrete blocks used in the construction of inner leaf walls 100 mm thick. The influence of moisture on compressive strength was significant and measures are therefore required to ensure walls are adequately protected to prevent wetting and excessive water absorption. Below a moisture content of 3.00 % the compressive strength of unfired clay units were suitable for the construction of non-load bearing walls. Ambient conditions, which simulate the conditions in domestic dwellings, result in moisture contents of approximately 2.00 % for these unfired clay materials, which is sufficient to ensure structural integrity of the extruded unfired clay units.

Specimens for the various sets of tests conducted gave different moisture contents after conditioning for 28 days under the controlled ambient conditions. This was due not due to differences associated with the specimen preparation method or differences in the shape and size of specimens tested but to a fault with the humidifier in the conditioning room. As a result conditions in the room were not constant with time. However, each series of tests were done on a batch of specimens conditioned over the same period of time allowing direct comparison of measurements. Measurements from different test series were compared indirectly as the differences in moisture contents needed to be accounted for.

Effect of perforations

Modifications such as perforations reduced the compressive strengths of the unfired clay units. Perforations of a larger size in direction of loading reduced compressive strength significantly more than those of a smaller size occupying the same surface area. Units with the perforations in the direction of loading are substantially stronger than those with the perforations at right angles to loading. Constructing with the perforations at right angles to the direction of loading should be avoided.

Following on from the above tests four standard extruded unfired clay brick units (220 mm × 105 mm × 69 mm) and their respective brick clays were sourced to establish suitable clays and locations to develop prototype unfired clay masonry units.

3.3 Properties of standard clays used for fired clay bricks

Representative samples of different brick clays (referred to as Soils 2, 3, 4 and 5) were analysed (BS 1377-2:1990). Soil 2 and Soil 3 was described as very clayey silt and fine to coarse sand with traces of fine gravel, similar to Soil 1 above. Soil 4 was described as very clayey silt and fine to coarse sand and Soil 5 as very sandy silt/clay.

Soils 4 and 5 contained significantly lower gravel contents than Soils 2 and 3 (Table 3.4 and Figure 3.4). Soils 2, 3 and 4 contained similar fractions of sand, silt and clay whereas the sand content of the Soil 5 was significantly lower and the silt and clay contents significantly higher. Soils 2 and 3 contained similar particles size fractions to Soil 1 (Table 3.4). Linear shrinkage, LL, PL and PI of Soils 1, 2, 3 and 4 were similar but lower than those of Soil 5 (Table 3.4 and Figure 3.5). This was due to the lower clay contents of Soils 1, 2, 3 and 4 than that of Soil 5 (Table 3.4 and Figure 3.5).

Soils were typical of the brick clays used for the manufacture of fired clay brick units (BIA, 2006 and Brick and Tile Industry, 2012). Soils were classified as clayey soils of low to intermediate plasticity. Clayey soils are required to give vitrification of the green brick units on firing. These soils allow for good extrusion to produce stiff green brick units with low shrinkage on firing and give fired clay brick units of good tolerances free from shrinkage cracks.

Table 3.4 Properties of standard brick clays

Brick Clay	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	LL (%)	PL (%)	PI (%)	Shrinkage (%)
Soil 1	4.2	36.0	34.6	25.3	37	18	19	9.6
Soil 2	5.8	35.4	33.8	25.0	37	17	20	8.6
Soil 3	7.7	34.1	32.0	26.2	36	17	19	9.0
Soil 4	0.3	36.6	38.1	25.0	37	18	19	8.9
Soil 5	1.0	23.6	41.2	34.3	44	20	24	10.4

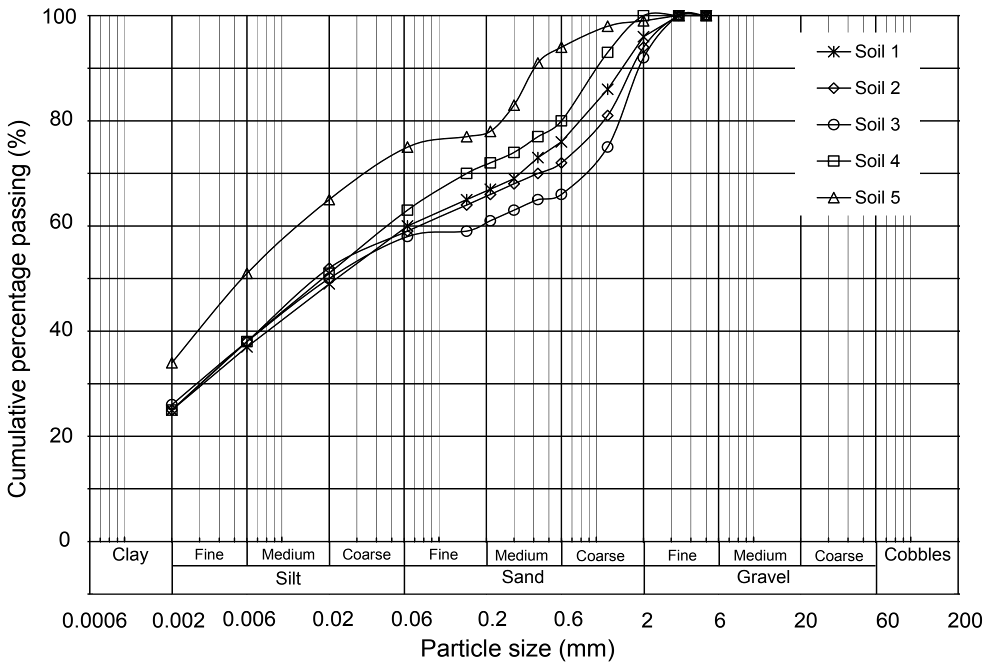

Figure 3.4 Particle size distribution curves of soils 1, 2, 3, 4 and 5

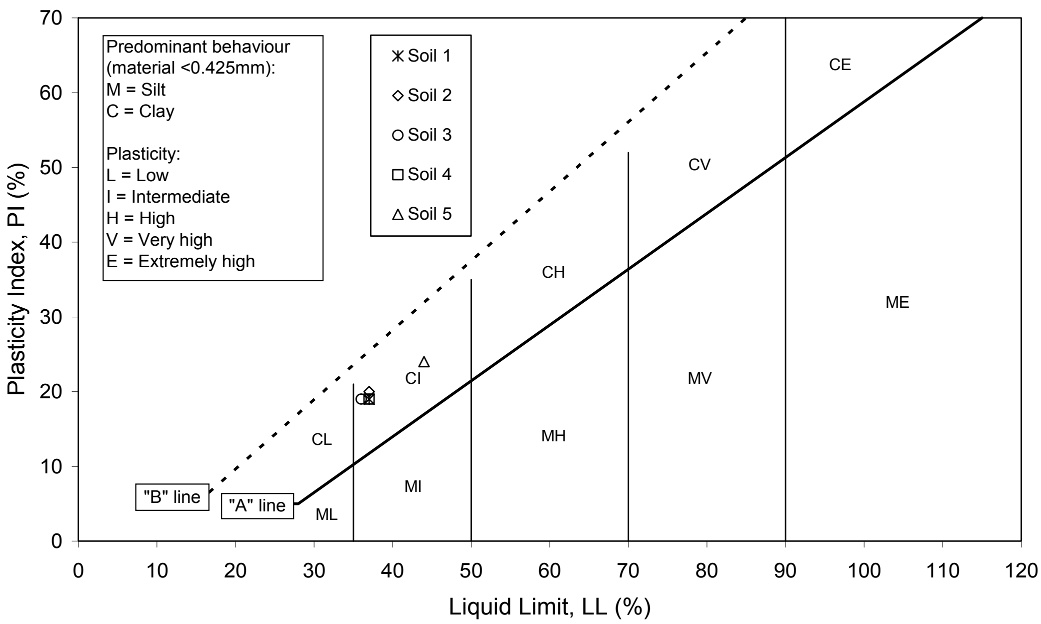

Figure 3.5 Classification and plasticity curve for Soils 1, 2, 3, 4 and 5

3.4 Properties of standard extruded unfired brick units

A series of measurements and tests were done on the four unfired clay brick units sourced (referred to as Units 2, 3, 4 and 5 extruded from Soils 2, 3, 4 and 5 respectively) and on unfired clay block units which were extruded from Soils 2 and 3 respectively. All tests were done according to British and European Standards used for fired clay brick units. The procedures were followed as close as possible but in certain cases the procedures needed to be adapted to suit properties of unfired clay brick units. The properties of the extruded unfired clay masonry units determined were:

- dimensions
- density
- compressive strength and flexural strength
- influence of moisture content on compressive strength
- influence of relative humidity on moisture content and compressive strength
- swelling and shrinkage (i.e. change in length versus change in moisture)
- air-drying times and water absorption rates
- screw pull-out loads

3.4.1 Dimensions

Dimensions (average of six determinations) were determined using the British Standard Method (BS EN 772-16:2000). Dimensions of the unfired clay brick units were all similar (Table 3.5). Dimensions of the green brick units were such that upon firing the units will shrink to that of the standard work size (215 mm × 102.5 mm × 65 mm) documented in the British Standard (BS 3921:1985). Units 2, 3 and 4 were all solid formats whereas the Unit 5 contained three large oval perforations with a major axis of 59 mm and a minor axis of 42 mm (Figure 3.6).

Table 3.5 Dimensions, dry density and net compressive and flexural strengths at 20° C and 60 % – 65 % RH of unfired clay brick units 2, 3, 4 and 5

Specimen	Dimensions			Density	Net Strength	
	Length (mm)	Width (mm)	Height (mm)	(kg/m^3)	Compressive (N/mm^2)	Flexural (N/mm^2)
Unit 2	227.0	106.8	69.2	2060	3.81	1.20
Unit 3	223.4	107.9	68.7	2063	3.88	1.10
Unit 4	228.8	108.6	68.9	2058	3.97	1.21
Unit 5	221.8	105.2	68.1	2022	6.93	1.89

3.4.2 Density

Density of the units was determined using the gross density method documented in BS EN 772-13:2000. Density (average of six determinations) of Units 2, 3 and 4 were higher than that of Unit 5 (Table 3.5). Unit 1 was of a similar density to Units 2, 3 and 4. Owing to the higher clay content Unit 5 was expected to have the highest density. However, saw-dust was mixed into the clay to assist with the firing of the green brick units which accounted for the lower density of Unit 5. Unit 5 was also Weald clay which has higher plasticity than the other clays (see Table 3.5).

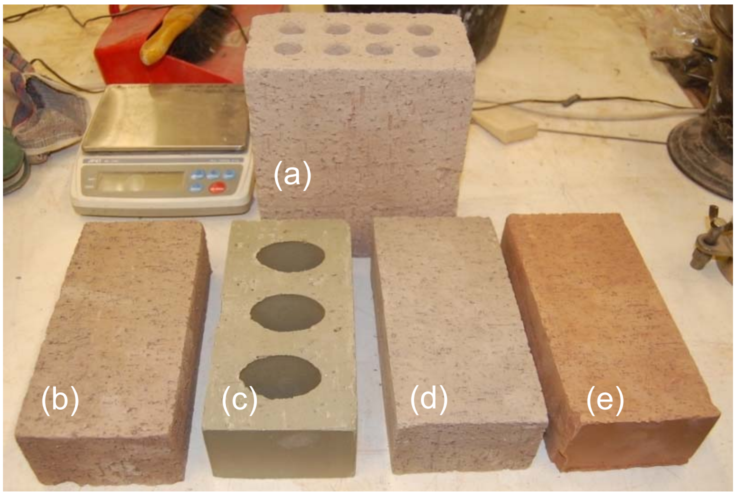

Figure 3.6 Unfired clay masonry units sourced (a) perforated half block cut from Block Unit 1 (b) Brick Unit 2 (c) Brick Unit 5 (d) Brick Unit 3 (e) Brick Unit 4

3.4.3 Compressive and flexural strengths

Compressive strength was determined directly on brick units capped with dental plaster using the standard method (BS EN 772-1:2000). Specimens were conditioned under ambient conditions for 28 days prior to testing. Specimens were loaded at a rate of 50 N/s until failure. The geometric factor that relates to specimen shape and size was not applied to normalise the compressive strength measurements. Flexural strength was determined on the brick units using a three point bending test. A load rate of 0.5 mm/min until failure was applied to the centre of the brick specimen supported at both ends.

Compressive strength (average of four determinations) and flexural strength (average of six determinations) of Unit 5 were substantially higher than those of the Units 2, 3 and 4 (Table 3.5). The higher strength of Unit 5 was directly related to the higher clay content of the material. Compressive strengths of all the units were acceptable for the construction of non-load bearing inner walls (i.e. strengths were above the minimum of 2.50 N/mm^2 required as stated in BS EN (NA) 1996-1-1:2005). All bricks failed in flexure and not shear.

3.4.4 Influence of moisture and humidity on compressive strength

Moisture affects the compressive strengths of all the brick units similarly. Strengths of the units decrease at similar rates with the increase in moisture content (Figure 3.7). The rates at which the strengths decreased diminished with the increase in moisture content of the brick units. Compressive strengths with moisture contents of Units 5 were consistently higher than those of Units 2, 3 and 4. Above moisture contents of 3.00 % the compressive strengths of Units 2, 3 and 4 were less than 2.50 N/mm^2 and not suited for the construction of thin non-load bearing walls (BS EN (NA) 1996-1-1:2005). Owing to the substantially higher compressive strength with moisture content of Units 5 the material remained suitable for construction of thin non-load bearing walls at moisture contents of 7.00 %.

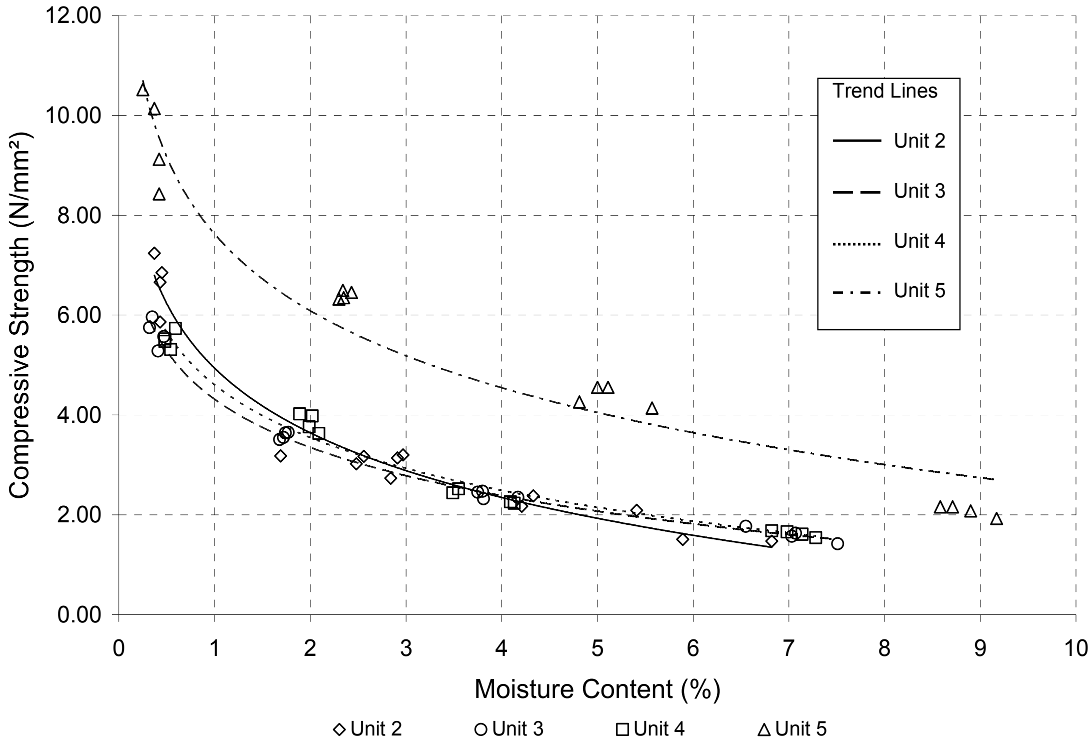

Figure 3.7 Compressive strength versus moisture contents for Units 2, 3, 4 and 5

The influence of relative humidity on the moisture contents and consequently compressive strengths of Units 2, 3, 4 and 5 were determined. Owing to the hydroscopic nature of the unfired clay the moisture content of the material changes with relative humidity. As a result, the compressive strength will change with relative humidity.

Moisture contents at different relative humidity levels were determined for the four unfired clay materials and compared to those determined for dense concrete block and fired clay-brick materials. A representative sample (approximately 100 g) was placed in a humidity chamber controlled at consecutive relative humidity levels of approximately 30 %, 40 %, 50 %, 60 %, 70 %, 80 %, 90 % and 100%. Specimens were left to stabilise with respect to moisture content (approximately 48 hours). After stabilisation the moisture contents of the specimens were determined. Compressive strengths at the different relative humidity levels for the four unfired clay materials were determined using the relationship between the compressive strength and moisture content determined above (refer to Figure 3.7).

Moisture contents of the unfired clay material from Units 2, 3 and 4 increased at similar rates with increasing relative humidity whereas the moisture content of the Unit 5 material increased at a significantly higher rate with increasing relative humidity (Figure 3.8). As a result, the moisture contents of the Unit 5 material were significantly higher than those of the materials from Units 2, 3 and 4. An increase in relative humidity from 30 % to 80 % gave a constant rate of increase in moisture content for the four unfired clay materials. After 80 % relative humidity the rate of increase in moisture contents of the unfired clay materials were exponential.

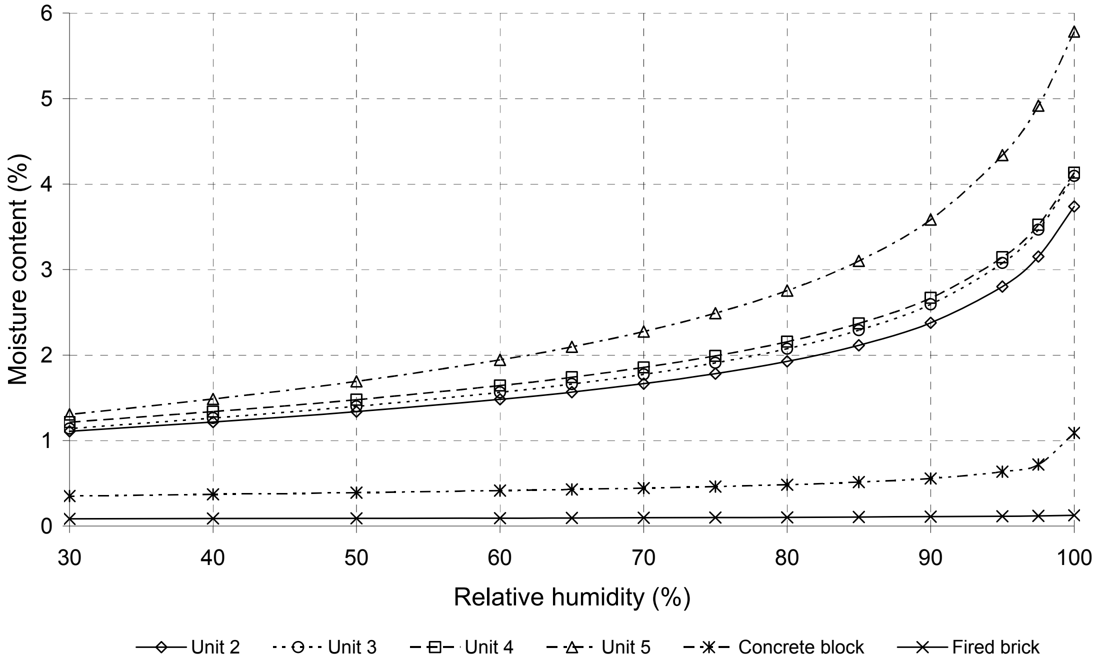

Figure 3.8 Moisture contents with relative humidity of materials from Units 2, 3, 4 and 5, dense concrete block and fired-clay brick

Moisture contents of the concrete block and fired clay-brick materials were substantially lower than those of the unfired clay materials (Figure 3.8). A slight increase in moisture content with the increase in relative humidity was measured for the concrete material whereas the moisture content of the fired brick material remained constant and negligible with increasing relative humidity.

Compressive strength of the four unfired clay materials decreased at similar rates with increasing relative humidity (Figure 3.9). The rate of decrease of compressive strength was constant with the increase in relative humidity from 30 % to 80 %. After 80 % relative humidity the compressive strengths decreased at an increasing rate with the increase in relative humidity. The decrease in compressive strength was directly related to the increase in moisture content (refer to Figure 3.7) of the unfired clay materials with the increase in relative humidity.

The increase in moisture content and consequent decrease in compressive strength with increasing relative humidity was due to the hygroscopic nature of the unfired clay materials. Clay readily absorbs moisture from the atmosphere. The amount of water absorbed depends on the equilibrium moisture content of the clay at a particular relative humidity (i.e. the higher the relative humidity the higher the rate of water absorption). The higher water absorption rate of the Unit 5 material than those of the Units 2, 3 and 4 materials with relative humidity was directly related to the higher clay content of the Unit 5 material. The higher moisture contents with relative humidity of the Unit 5 material did not result in lower compressive strengths as the higher clay content also accounts for the higher compressive strength of the Unit 5 material than those for the Units 2, 3 and 4 materials.

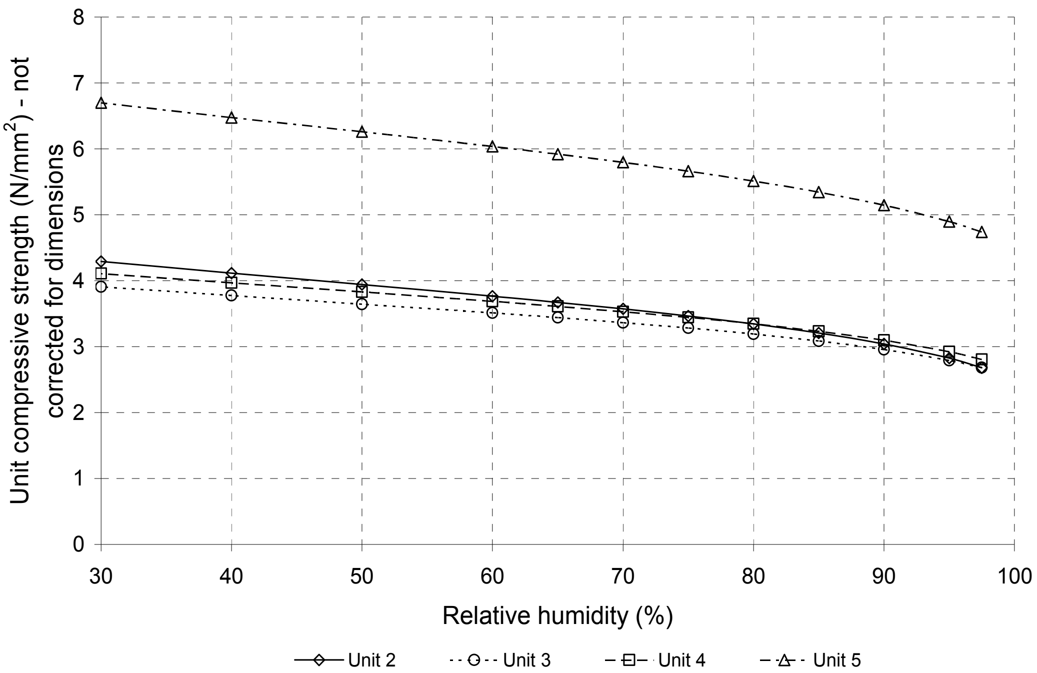

Figure 3.9 Compressive strength of Units 2, 3, 4 and 5 with relative humidity

The increase in moisture content of the unfired clay materials with increasing relative humidity was not critical as even at a relative humidity of 100 % the compressive strengths of the unfired clay materials were above the 2.50 N/mm^2 required for the construction of thin non-load bearing walls.

3.4.5 Swelling and shrinkage

Change in length of the brick specimens (average of four determinations) was directly proportional to the change in moisture that is specimens shrank at a constant rate during drying (Figure 3.10). Shrinkage of Unit 5 was significantly lower than that of the Units 2, 3 and 4. Shrinkage is important to consider during the mortaring and plastering of the unfired brick walls. Standard application of mortars and plasters allows for up to 2 % absorption of moisture. Swelling caused with moisture absorption develops internal stresses in the bricks causing cracks. On drying excessive shrinkage causes breakages of the mortar/plaster bond.

3.4.6 Air-drying times and atmospheric moisture absorption

Air-drying times of Units 2 after extrusion were assessed to estimate time required to dry units to a moisture content giving compressive strengths acceptable for construction. Absorption of moisture into oven-dried units was also assessed to determine time required for units to stabilise with respect to moisture content and compressive strength.

Standard solid brick sized units and solid and perforated block sized specimens (225 mm × 106 mm × 225 mm) cut from extruded blocks (370 mm × 106 mm × 225 mm) were tested. Perforations were drilled into the blocks sized specimens (8 × 25 mm diameter perforations). Specimens were left to dry under ambient conditions until a constant moisture content and compressive strength was attained with time. Specimens were dried in an oven at 105 °C until a constant mass was achieved. Specimens were then left under ambient conditions until moisture content and compressive strength remained constant with time.

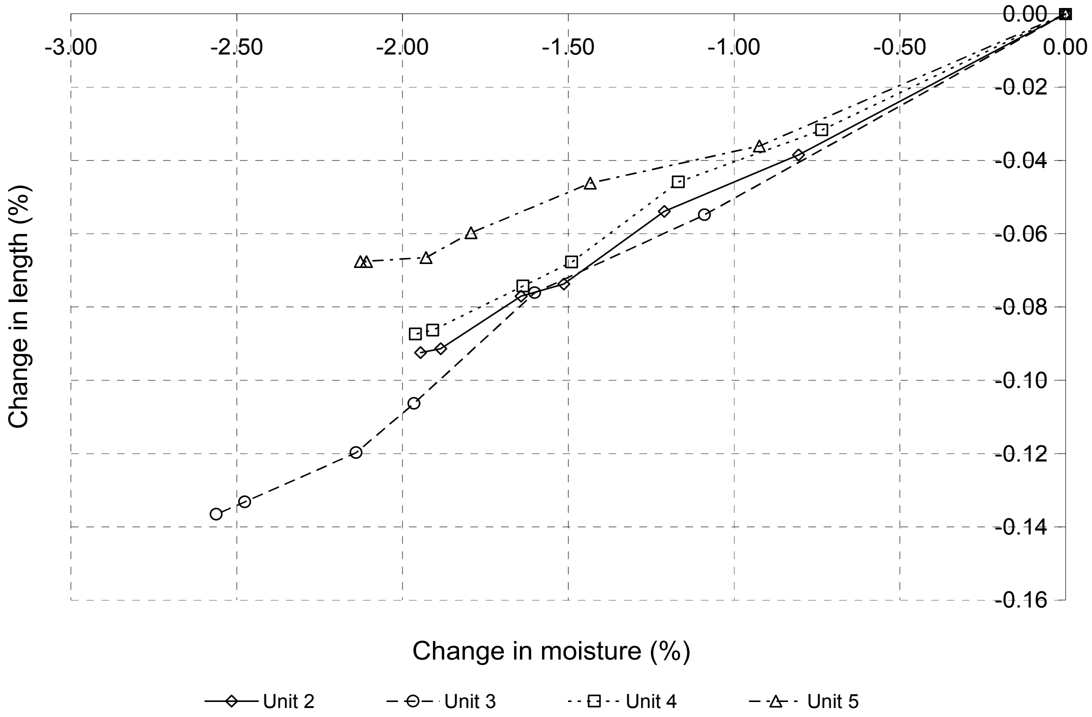

Figure 3.10 Change in length with moisture for Units 2, 3, 4 and 5

Size and perforations of units affected air-drying times. Standard solid brick units and perforated block units achieved acceptable moisture contents and strengths after 10 days whereas solid block units only reached acceptable strengths after 21 days (Figure 3.11). Oven dried solid brick and block units stabilised after 21 days.

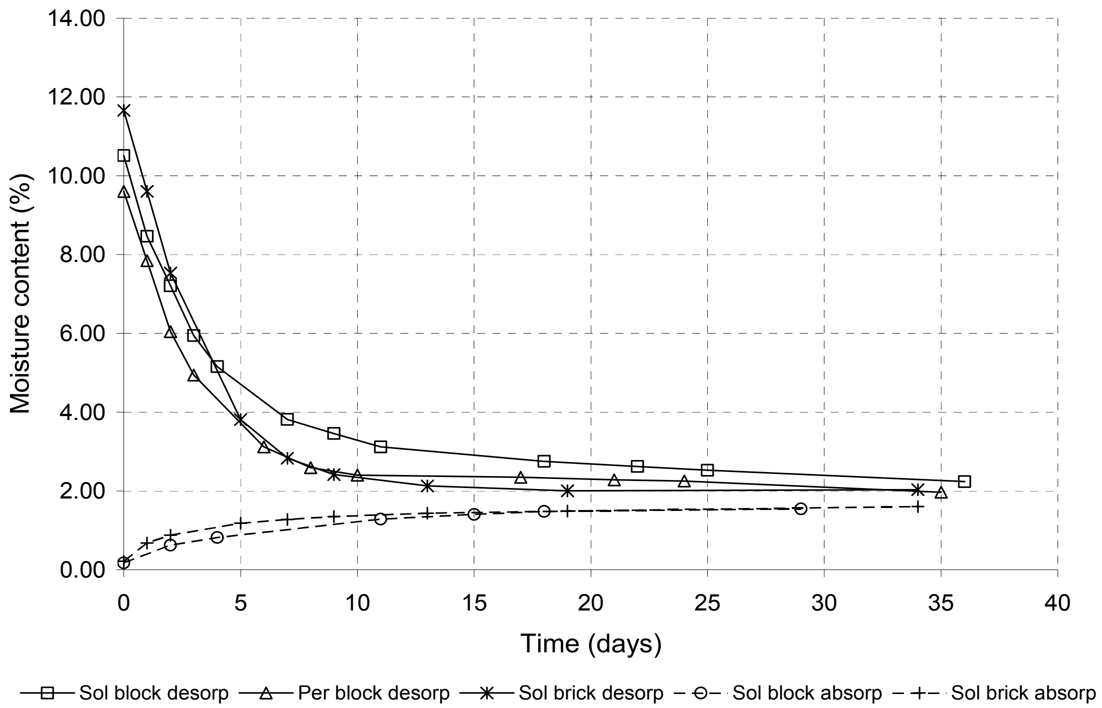

Figure 3.11 Stabilisation times of solid and perforated Unit 2 brick and block specimens at ambient conditions (20 °C and 60 % - 65 % RH)

3.4.7 Screw pull-out loads

A rudimentary investigation was done on Units 2, 3, 4 and 5 to assess the suitability of fixings into the unfired clay material. Screw-pull out tests were done on gauge 10 screws (i.e. 5 mm in diameter) inserted into 7 mm diameter plastic masonry wall plugs. Screws were pulled-out at a rate of 1 mm/min. Screws were inserted into the solid and perforated areas of Unit 5.

A load of approximately 0.80 kN was required to pull-out the screw/wall-plug in all of the brick units except for those inserted into the perforations in Unit 5. A substantially lower force of approximately 0.40 kN was required to pull-out the screw here. A few tests on each unit were only possible as inserting the screw caused some of the bricks to crack. Unit 5 was particularly susceptible to cracking due to the presence of the large perforations. Such stresses are absorbed when screws are inserted into a wall and standards require that screws be placed at adequate distances from wall edges and each other to compensate for these stresses. More rigorous testing to assess suitability of fixings was to be done on wall panels once the prototype blocks were manufactured.

3.4.8 Concluding remarks and discussion

All brick units had suitable strength for the construction of thin non-load bearing walls. Strengths of Units 5 were better than those of the Units 2, 3 and 4. It is speculated that this is related to the higher clay content of Soil 5. The lower density of Units 5 was due to the different soil type, the inclusion of saw-dust into the clay mixture and the method used to determine the volume of the material in the brick units. The volume of the material was calculated from the dimensions of the brick units measured minus the volume of the perforations, which was estimated from the major and minor axes measured. The lower swelling and shrinkage of Units 5 compared to that of Units 2, 3 and 4 was due to the perforations in Units 5. As a result, Units 5 contain substantially less material than Units 2, 3 and 4 and will therefore swell and shrink less with the absorption and de-sorption of water.

The influence of moisture content on the strength of the unfired clay masonry units is the most critical factor to consider. The moisture content has a large influence on compressive strength of the unfired clay material. Moisture contents above 3.00 % could give strengths that are not suitable for the construction of thin walls. Ultimately this depends on the strength of the material such as observed with Units 5, which gave strengths suitable for construction at water contents well above 3.00 % (i.e. up to 7.00 %).

Water absorption at relative humidities above 90 % could increase moisture contents to above 3.00 % and give compressive strengths unsuitable for construction. However, it is only the outer layer of unfired clay masonry units (10 mm to 20 mm) that are affected by water absorption dependant on the relative humidity (Minke, 2007 and Morton 2008). Structurally unfired clay masonry units could therefore still resist the forces on a thin non-load bearing wall at a relative humidity above 90 %.

The results indicated that masonry units extruded using Soil 5 gave better performance than those extruded using Soils 1, 2, 3 and 4. Doing a trial to produce a prototype block at the factory using Soil 5 was not a viable option as the “Specials plant” at the factory was closed during the course of this project. The factory was only running a high-capacity main plant and not a low-capacity specials plant which could be used to manufacture non-standard units. The factory using Soils 2, 3 and 4 was running a plant capable of producing smaller quantities of special masonry units (3 000 brick units per hour), which was more suited to running a trial than the main plant used for mass production of brick units (10 000 units per hour). It was decided to use Soil 2 to develop the prototype unfired clay blocks. Soil 2 was the most abundant brick clay and Unit 2 gave slightly better properties than Units 3 and 4 particularly with respect to the influence of moisture content on the compressive strength.

3.5 Properties of brick clay units containing plant fibres

Unfired clay masonry units are friable and need to be strengthened to reduce breakages during the transport and handling and to improve the capacity of fixings. Modifications with plant fibres such as straw and wood fibres were considered to improve on toughness (i.e. handling and transport properties) of the unfired clay units and to strengthen the material namely to improve on the properties of perforated units and fixing strengths into the units. A series of tests were conducted on specimens with and without plant fibres to determine and compare:

- density
- compressive and flexural strength
- swelling and shrinkage
- durability and toughness

3.5.1 Materials

The effect of the plant fibres on the properties of the unfired brick clays was assessed using Soil 2. Straw and two wood-fibres namely that used for the manufacture of medium density fibre board (MDF) and that used as a growth medium (GMF) were used in the investigation (Figure 3.12).

Figure 3.12 Plant fibres a) MDF wood-fibre, b) processed straw, c) technical grade hemp d) GMF wood-fibre

Straw is tough and waxy and needs to be refined to be suitable for use in the extrusion process (i.e. to improve binding properties and minimise impact on wire-cutting process used). Straw was cut into 5 cm lengths and chopped further in a food processor to 10 to 20 mm lengths. The chopped straw was then blended in water to obtain fibres of 3 to 20 mm in length. The wet fibres collect were dried in an oven at 40°C.

MDF is processed using a thermo-mechanical refiner. Softwood chips are softened in water and then refined under elevated temperature and pressure between a set of rotating discs which grind the chips into fibres less than 10 mm in length. GMF is processed at room temperature and atmospheric pressure using a mechanical refiner which grinds the wet softwood chips into fibres less than 20 mm in length. GMF is a coarser grade of fibre and are not as reactive as the MDF fibres (Figure 3.12).

3.5.2 Specimen preparation

A hand-extrusion device was used to prepare the test specimens (Figure 3.13). The device consists of a vertically wall-mounted cylinder (85 mm diameter × 300 mm high), a plunger with lever, a restricting cone (85 mm to 50 mm diameter) mounted at the base of the cylinder and die-housing clamped to the bottom of the cylinder.

Figure 3.13 Hand extrusion device

Clay at water content close to its plastic limit (approximately 17 % for Soil 2 without any fibre) was mixed in a pan mixer and then compacted using the plunger in the cylinder of the hand extruder, which was sealed with a solid plate fitted into the die-housing. The cylindrical clay specimen was removed and the inverted-cone was positioned inside the cylinder and inserted into a circular die (50 mm in diameter) clamped to the bottom of the cylinder. The clay specimen was re-inserted into the cylinder and forced into the inverted cone and extruded through the circular die. Clay specimens of approximately 300 mm in length were extruded and air-dried for 24 hours. Specimens were dried at 40 °C for 3 days to prevent shrinkage cracks prior to drying at 105 °C for 24 hours. Specimens for testing were sawn from the oven dried specimens.

Water contents of mixtures containing fibres were increased to give similar consistency on mixing, compaction and extrusion to that of the mixture without fibre. Fibres were added in quantities of 1 %, 2 % and 3 % by weight. Clay and fibre were mixed dry in a pan mixer prior to adding water to ensure dispersion of the fibre throughout the mixture. Water demand increased with plant fibre content. Water content at 1 %, 2 % and 3 % fibre was approximately 19 %, 20 % and 22 % respectively. Straw and MDF were easily dispersed throughout the dry soil and throughout the wet clay. GMF required more effort to disperse homogeneously.

3.5.3 Density, compressive and flexural strength

Compressive strength (average of 12 determinations) was determined on cylindrical specimens (50 mm diameter × 50 mm high) capped with dental plaster (BS EN 772-1:2000). Specimens were loaded at a rate of 0.5 mm/min until failure. Flexural strength (average of 8 determinations) of cylindrical specimens (50 mm diameter × 150 mm high) was determined using the three point bending test method. Specimens were loaded at a rate of 0.5 mm/min until failure (Figure 3.14). Density (average of 20 determinations) was determined on the cylindrical specimens prepared for compressive and flexural strength tests using the gross density method documented (BS EN 772-13:2000).

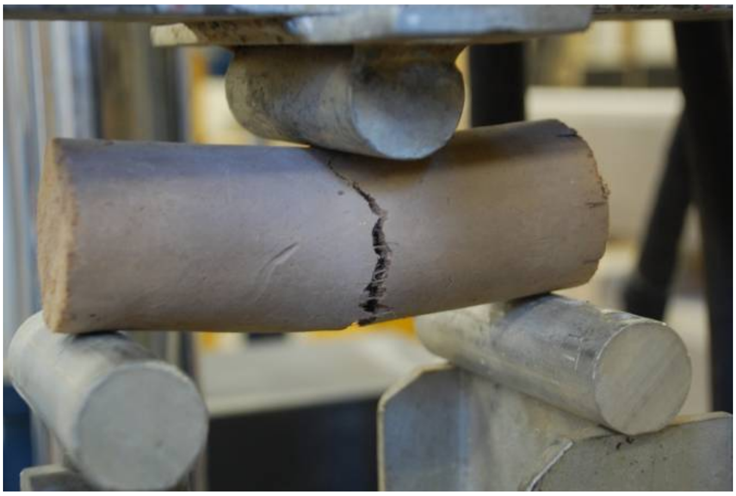

Figure 3.14 Three point bending test of cylindrical specimen (50 mm diameter × 150 mm long) to determine flexural strength

Specimens without plant fibre were of a higher density (2034 kg/m^3) and compressive strength (2.69 N/mm^2) but similar flexural strength (1.18 N/mm^2) to those of Units 2, i.e. the brick units extruded using Soil 2 (2060 kg/m^3, 3.81 N/mm^2 and 1.20 N/mm^2 respectively). Adding plant fibre substantially lowered the density of the extruded clay specimens (Table 3.6). Density decreased with plant fibre content. Straw lowered the density to a substantially larger degree than the wood-fibre. The lowering of density can reduce thermal conductivity and potentially reduce heat loss.

Table 3.6 Density, compressive strength and flexural strength of hand-extruded specimens

Specimen	Density (kg/m^3)	Compressive (N/mm^2)	Flexural (N/mm^2)
0 % fibre	2034	2.69	1.18
1 % GMF	1960	2.44	1.05
2 % GMF	1901	2.62	1.35
3 % GMF	1828	2.08	0.84
1 % MDF	1938	2.96	1.28
2 % MDF	1891	2.71	1.23
3 % MDF	1825	2.55	1.35
1 % Straw	1913	1.84	1.04
2 % Straw	1801	2.00	0.96
3 % Straw	1703	1.34	0.88

Compressive strength of the 1 % GMF, 3 % GMF and 3 % MDF specimens were lower than those of the specimens without plant fibre. Compressive strengths of the 2 % GMF and 2 % MDF specimens were similar to that of the specimens without plant fibre and that of the 1 % MDF specimens were higher. Compressive strengths of the straw specimens were substantially lower.

Flexural strengths of the 1 % GMF, 1 % straw and 2 % straw specimens were lower than that of the specimens without plant fibre and those of the 3 % GMF and 3 % straw specimens were substantially lower. Flexural strength of the 2 % GMF, and 3 %, 2 % and 1 % MDF specimens were substantially higher than that of specimens without plant fibre.

3.5.4 Swelling, shrinkage and air-drying rates

Swelling and shrinkage (i.e. change in length with change in moisture) of the plant fibre and non-plant fibre specimens were similar. Specimens containing the plant fibre dried at slightly faster rates than those without plant fibre.

3.5.5 Durability and toughness

A rudimentary investigation was conducted on the specimens containing the plant fibres to assess the effect of the plant fibre on fixings, packaging, transport and handling. Drop tests were done on the cylindrical specimens (approximately 200 g in weight) to ascertain durability and toughness important factors to consider for packaging, transport and handling of blocks. A 5 mm masonry wall plug was inserted into the cross-sectional face of the plant fibre and non-plant fibre specimens (50 mm diameter × 80 mm length) to determine resilience to fixings.

Specimens with 2 % wood fibre contents (both MDF and GMF) dropped from a height of 2 m onto a smooth concrete floor cracked whereas the non-plant fibre and 2 % straw specimens shattered. Constant dropping of specimens from approximately 0.6 m onto the concrete floor revealed that the 2 % wood fibre and 2 % straw specimens were substantially more resilient than the non-plant fibre specimens. Gravel to stone size chips broke of the edges of the non-plant fibre specimens at each drop whereas edges of the wood fibre and straw specimens crumbled slightly. After 9 to 12 drops the non-plant fibre specimens spit and the wood fibre specimens only showed signs of crumbling at the edges

(Figure 3.15). Straw specimens were chipped at the edges. Cracks were evident in the straw and wood fibre specimens. After 12 to 15 drops the straw specimens split. Wood fibre specimens split after 18 to 21 drops (Figure 3.15).

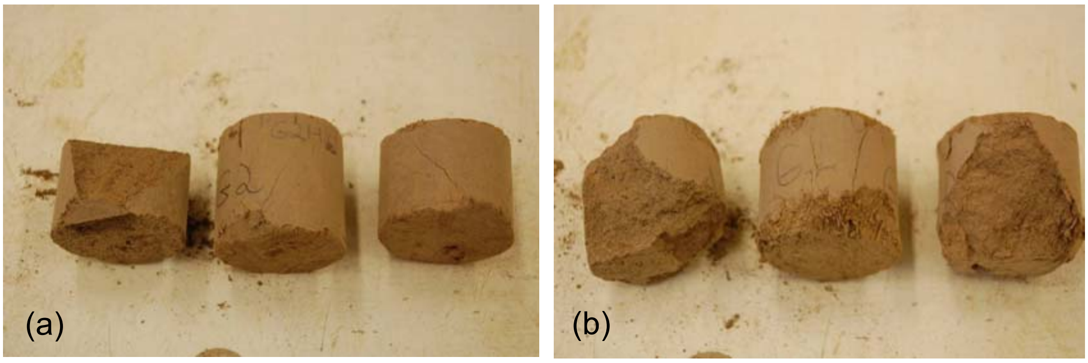

Figure 3.15 Specimen appearances when dropped from a height of 0.6 m (a) from left to right non-fibre, 2 % GMF and 2 % MDF specimen after 9 drops and (b) from left to right non-fibre after 9 drops, 2 % GMF after 18 drops and 2 % MDF after 18 drops

On screwing in a 5 mm diameter screw the non-plant fibre specimens immediately split in two. All of the plant fibre specimens (i.e. 1 %, 2 % and 3 % straw and wood fibre specimens) showed no signs of cracking even when the screw was fully inserted (approximately 15 mm). This implies that fittings into blocks containing plant fibre would be more secure.

3.5.6 Concluding remarks and discussion

Wood fibre and straw improved on durability and toughness, and decreased the drying rates and weight of the unfired clay specimens. Straw led to a significant decrease in the compressive and flexural strength of the unfired clay specimens. This decrease would render unfired clay blocks unsuitable for the construction of thin non-load bearing walls. Wood fibre did not significantly affect the compressive and flexural strength of the unfired clay specimens and would therefore be suitable for use in the manufacture of unfired clay blocks.

Results indicate that MDF was better suited for the manufacture of unfired clay blocks than GMF. MDF gave better improvement in the properties of the unfired clay specimens. This was ascribed to the manner in which the wood fibres are produced. The thermo-mechanical method used to manufacture MDF generates a tough fine wood fibre which was easily dispersed throughout the clay mixture. The mechanical method used to refine GMF gives a weaker coarser wood-fibre and in addition to this the wood fibres were vacuum packed making them more difficult to disperse throughout the clay mixture. GMF will therefore have a higher impact on the manufacture of the unfired clay blocks and give blocks of a poorer quality than those manufactured using MDF. However both MDF and GMF are suitable for the manufacture of unfired clay blocks. A method in which to separate and disperse the wood fibre into the clay mixture was needed to ensure optimum improvements in the properties of the unfired clay blocks.

Advantages from the plant fibre addition such as weight reduction, which makes handling the blocks more manageable and improvement in the air-drying rate of blocks are beneficial, but the main advantage was the improvement in toughness as observed when the plant fibre specimens were dropped and also when cut and tested for flexural strength. Sawing the specimens containing plant fibres required more effort than those without plant fibres and the plant fibre specimens continued to resist loading after the ultimate flexural strength was reached (Figure 3.16) whereas non-plant fibre specimens instantly failed at the ultimate flexural strength.

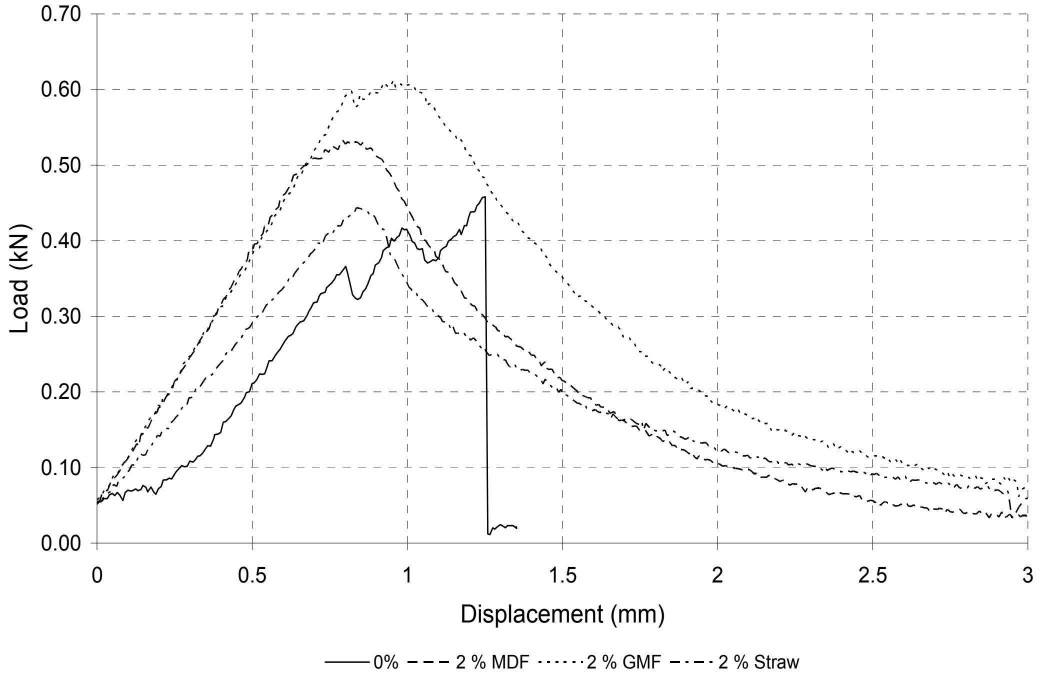

Figure 3.16 Load versus displacement of plant fibre and non-plant fibre unfired clay specimens (50 mm diameter × 150 mm length) measured using the three point bending test method (one specimen per material tested)

Toughness is important as it not only improves handling, transport and fixing properties but also makes the unfired clay units more resilient to the inherent stresses developing in the units on plastering of walls. Water absorbed into the unfired clay from the plaster causes swelling and in thin-wall structures plastered on one side the stresses that build-up are sufficient to crack the wall.

In summary, wood fibres are best suited for use in unfired clay masonry units:

- compressive and flexural strength are not affected
- air-drying rates are improved
- toughness increases
- shrinkage and swelling are not affected
- stresses during mortaring and plastering are absorbed
- weight of the block is reduced
- carbon lock-up is achieved
- material remains recyclable
- appearance is more appealing
- value is increased
- water transport properties are improved

Disadvantages of using wood-fibres:

- decreases thermal mass
- not ready available in the UK
- expensive to import
- increases embodied energy (fuel to manufacture and transport)
- storage problems and risk of fire hazard
- hamper production of units (feeding into process and wire cutting of units)

Wood fibre is expensive (£ 300/tonne) as no local source is available and it is currently shipped from abroad. A future option, if it proves feasible to use in unfired clay units, is to manufacture the wood fibre locally from wood chips (costing £ 80/tonne). Hemp and flax fibre are other options. Although hemp is available locally the technical grade required is costly (similar in price to the imported wood fibre) and it also requires further processing to obtain short fibre lengths (less than 10 mm) required to minimise the interference of the fibres during the wire cutting process used to slice the extruded clay. Flax is imported and would therefore cost as much as wood-fibre (£250/tonne) and it also requires de-baling and further processing to produce fibres of the required lengths.

3.6 Conclusions from all initial testing

All unfired clay brick units sourced were suitable for the construction of inner non-load bearing thin-walls. Brick units 5 has a higher strength and lower drying shrinkage than brick units 1, 2, 3 and 4 which indicates this could be the preferable source from a technical viewpoint. Owing to the absence of a specials plant capable of producing lower volumes of units than the main plant, a trial or limited production was not feasible at the factory manufacturing brick units 5. Brick clay 2 was best suited for a trial as it gave slightly better properties than clays 1, 3 and 4 and was the most abundant and the factory has a first-class specials plant capable of producing small quantities of masonry units. It was evident from the tests that the unfired brick units behave in a similar manner and that once a prototype unfired clay block has been formulated it could be produced at any of the factories or with any clay used for the extrusion of brick units.

The geometric correction factors stated in the British Standard Test Method for the measurement of compressive strength do not apply to the unfired clay masonry units, that is shape and size of the masonry units do not significantly influence the compressive strength measurements, possibly because of the low strength compared to fired clay masonry units

Perforations in the unfired clay masonry units significantly reduced the compressive and flexural strength. Perforations running in the direction of loading are likely to give strength acceptable for the construction of thin non-load bearing walls. Strengths of unfired clay masonry units with perforations at 90° to the direction of loading were substantially reduced making these units unsuitable for the construction of walls.

Strengths were not affected by the direction of extrusion. Strengths were similar in the direction of extrusion and at 90° to the direction of extrusion.

An increase in moisture content significantly reduced the compressive strength of unfired clay units. A sharp decrease in strength occurred from the oven dry state to that at ambient conditions where the moisture content was approximately 2 %. Strengths of the unfired clay masonry units at moisture contents from 2 % to 3 %, typical of those when plastering and when used in domestic dwellings, were adequate for the construction of non-load bearing walls.

Wood fibre was best suited to improve the properties of the unfired clay units. Compressive and flexural strength of the unfired clay specimens were not affected and the toughness of the specimens was significantly improved. Straw improved toughness but substantially reduced the compressive strength of the specimens which could render masonry units unsuitable for the construction of walls. Indications from the industrial partner in the project were that the inclusion of plant fibres may also impart more value to the unfired clay masonry units as they will appear to have increased performance.

A trial using brick clay 2 was required to determine the feasibility of adding wood fibre into the unfired clay and to determine the influence of wood fibres and perforations on the properties of the extruded unfired clay masonry units. The masonry units should be of a size and shape representative of the intended production blocks (440 mm × 215 mm × 100 mm). Solid and perforated blocks with and without wood fibre are required to ascertain the influence of perforations and wood fibre on the properties of the unfired clay masonry units. A mortar was also required for the construction of wall panels to determine the suitability of the unfired clay masonry in the construction of thin non-load bearing walls.

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CHAPTER 4

DEVELOPMENT OF AN UNFIRED CLAY MORTAR

4.1 Introduction

A mortar forms an integral part in the construction of thin walls and is not merely a bedding material for the masonry units as in traditional thick walls. A mortar must bond the masonry units in a thin wall together firmly to give the wall the strength to resist compressive and lateral loads. To maximise the performance of a thin wall, the mortar bond strength must be of similar or higher strength than the strengths of both the mortar and masonry units to prevent de-bonding along the interfaces between the mortar and masonry units. Ideally the strength of the mortar should be related to that of the masonry units. A mortar of lower strength is preferred as a mortar of higher strength results in fracture through the masonry units, which is difficult and costly to repair.

A suitable mortar to give the wall maximum strength in compression and tension is required for the unfired clay masonry units. Clay/sand mortars and conventional cement and lime based mortars give weak bond strengths (less than 0.2 N/mm^2) with unfired clay masonry units (Lawrence et al, 2008a, b and Walker, 2008). Clay/sand mortars are of a low strength and bond poorly to the unfired clay masonry units. Conventional cement and lime based mortars fail to form a good bond to the surfaces of the unfired clay masonry units. These mortars joints will not withstand lateral loads on the 100 mm thick walls used in mainstream construction, which require characteristic mortar bond strengths of greater than 0.2 N/mm^2 (BS EN (NA) 1996-1-1:2005 i.e. Eurocode 6) and are therefore not suitable for construction of thin-wall unfired clay masonry.

Mortars developed from brick clays containing sodium lingo-sulphonate gave better bond strengths but still lower than that required (Lawrence et al, 2008a, b). A PVA bonding agent used in conjunction with the conventional mortars and the lingo-sulphonate clay mortars gave characteristic bond strengths greater than 0.2 N/mm^2 (Heath et al, 2007). A commercially available sodium silicate mortar and mortars developed using brick clays and sodium silicate gave characteristic bond strengths in excess of the 0.2 N/mm^2 required (Lawrence et al, 2008a, b).

The objective of this chapter is to document and discuss the work done to develop mortars suitable for the construction of thin walls using the extruded unfired clay brick units sourced (i.e. to develop mortars of strengths and bond strengths similar to that of the extruded unfired clay brick units that will remain stable with time). Owing to the success in previous work (Lawrence et al, 2008) sodium silicate mortars were developed using the respective brick clays. The use of lingo-sulphonate was disregarded as these mortar bond strengths were found to deteriorate with time and give inferior bond strengths with certain clay types (Heath et al, 2007, Lawrence et al, 2008, Walker 2008). Application of the PVA is also not ideal as it slows construction and is expensive.

A thin-bed mortar (i.e. from 2 mm to 5 mm thick) was required to minimise the impact the mortar has on the properties of the masonry, reduce cost and minimise the embodied energy and embodied carbon of the masonry. The mortars must be easy to manufacture, workable and easy to apply. Mortars must preferably be of low embodied energy and embodied carbon, be reusable or recyclable and have a low impact on the environment. The work and testing done was to determine:

- clay, sand and water contents of the mortars
- shrinkage of mortars on drying
- sodium silicate contents of the mortars
- setting and drying times of the mortars
- mortar bond strengths
- influence of clay and sand coarseness (i.e. particle sizes of clay and sand required in the mortars) and sand content (i.e. leanness of the mixture) on mortar bond strengths
- mortar application thicknesses and methods

4.2 Method used to determine mortar bond strengths

Mortar bond strengths were measured using the flexural bond wrench test apparatus developed (Figure 4.1) (Heath et al, 2008) and the standard bond wrench test procedure (BS EN 1052-5:2005). Stacks four brick units high (i.e. containing three mortar joints) were prepared. Stacks were conditioned at 20 °C and 60 – 65 % RH (i.e. at ambient conditions) and tested at various ages, for example, after 1 day, 3 days, 7 days, 14 days, 28 days and 91 days). A minimum of four stacks (i.e. twelve mortar joints) were tested to achieve a representative average of bond strength measurements and calculated characteristic bond strengths. The standard requires the testing of a minimum of 10 joints. After testing nine joints the calculated average and characteristic bond strengths remain fairly constant (Figure 4.2).

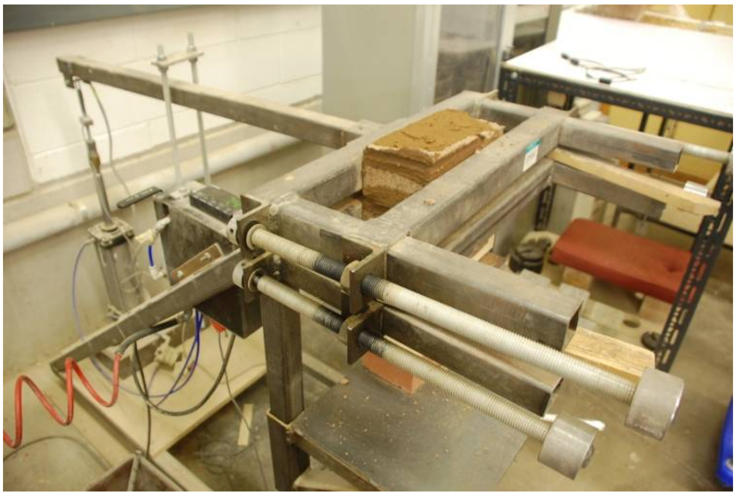

Figure 4.1 Mortar bond wrench test apparatus showing the clamping of the brick stack

4.3 Bond strengths of a commercial sodium silicate mortar

A preliminary investigation was done on Units 2, 4 and 5 to determine the suitability of a sodium silicate mortar on extruded unfired clay brick units using the 10 % by dry mass sodium silicate mortar available commercially. Stacks were prepared using mortar beds approximately 3 mm thick that were laid with a trowel. Stacks were conditioned at 20 °C and 60 % - 65 % RH for 8 days prior to the determination of mortar bond strengths. Good bond strengths (average of 12 joints) were achieved for all the brick units (Table 4.1). Characteristic bond strengths for all the units were higher than the 0.2 N/mm^2 required for thin-wall construction.

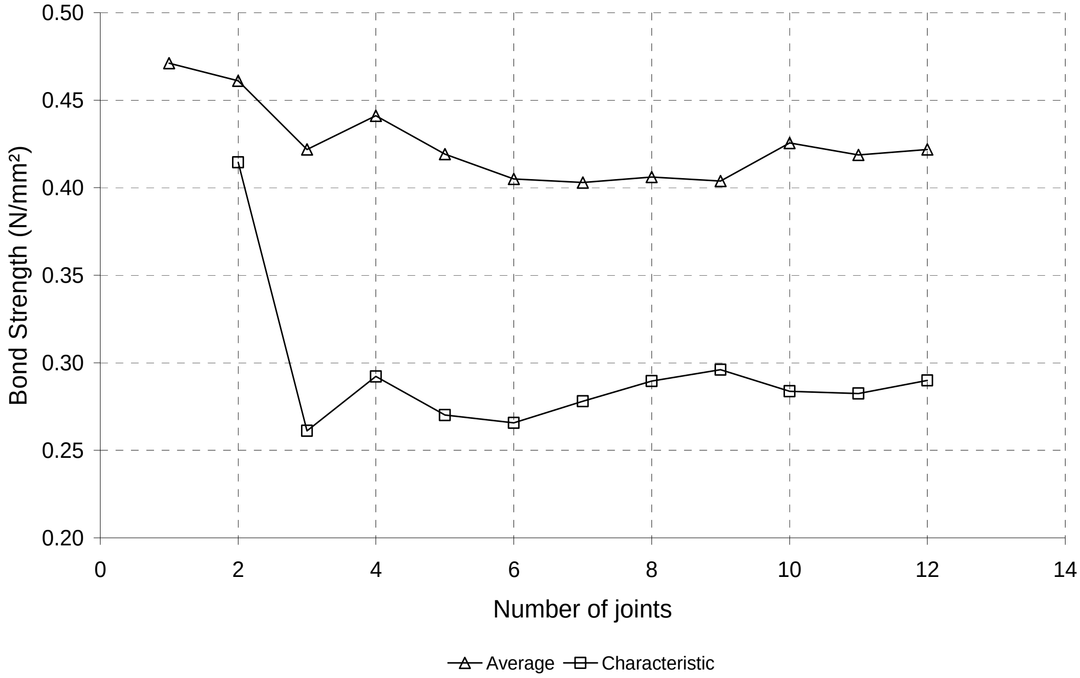

Figure 4.2 Variability of average and characteristic bond strengths with the number of mortar joints tested for Unit 2 stacks prepared with the 10 % commercially available sodium silicate mortar and conditioned for 8 days at 20 °C and 60 % - 65 % RH

Table 4.1 Bond strengths of the commercial sodium silicate mortar after conditioning at ambient conditions for 8 days (Stdev – standard deviation, Range – difference between lowest and highest values measured)

Unit	**Bond Strength** (N/mm^2)			
	Mean	Characteristic	Stdev	Range
Unit 2	0.51	0.33	0.11	0.34
Unit 4	0.57	0.37	0.12	0.33
Unit 5	0.40	0.26	0.09	0.31

All failures were either through the brick units or from the brick delaminating onto the mortar at the bond interface (Figure 4.3). This indicates that the bond was stronger than both the mortar and the extruded brick units. Average and characteristic bond strengths were lower for Units 5 than for Units 2 and 4. This was due to the perforations in Units 5 which reduces the surface of bonding and act as stress raisers to initiated failure when wrenching. A poorer compatibility of Units 5 with the mortar may also influence the bond strengths. Statistically (t-Test: Two-Sample Assuming Unequal Variances) there was a significant difference between the average bond strength of Units 5 and those of Units 2 and 4 whereas there was no significant difference between the average bond strengths between Units 2 and 4.

Sodium silicate based mortars are available commercially as fireproof mortars but these are very expensive as the mineral fillers (sand and fines) also need to be fireproof. A plain clay/sand mortar with a sodium silicate content of 10 % or even lower should be capable of giving the characteristic bond strengths required for thin wall earth masonry construction at a lower cost than for fireproof mortars.

4.4 Bond strengths of sodium silicate clay mortars

An investigation into the suitability of sodium silicate clay/sand mortars was done using mortars developed from brick clays 2 and 5 (i.e. Soils 2 and 5) to determine sodium silicate content and the strength and stability of the mortar and the mortar bond with time.

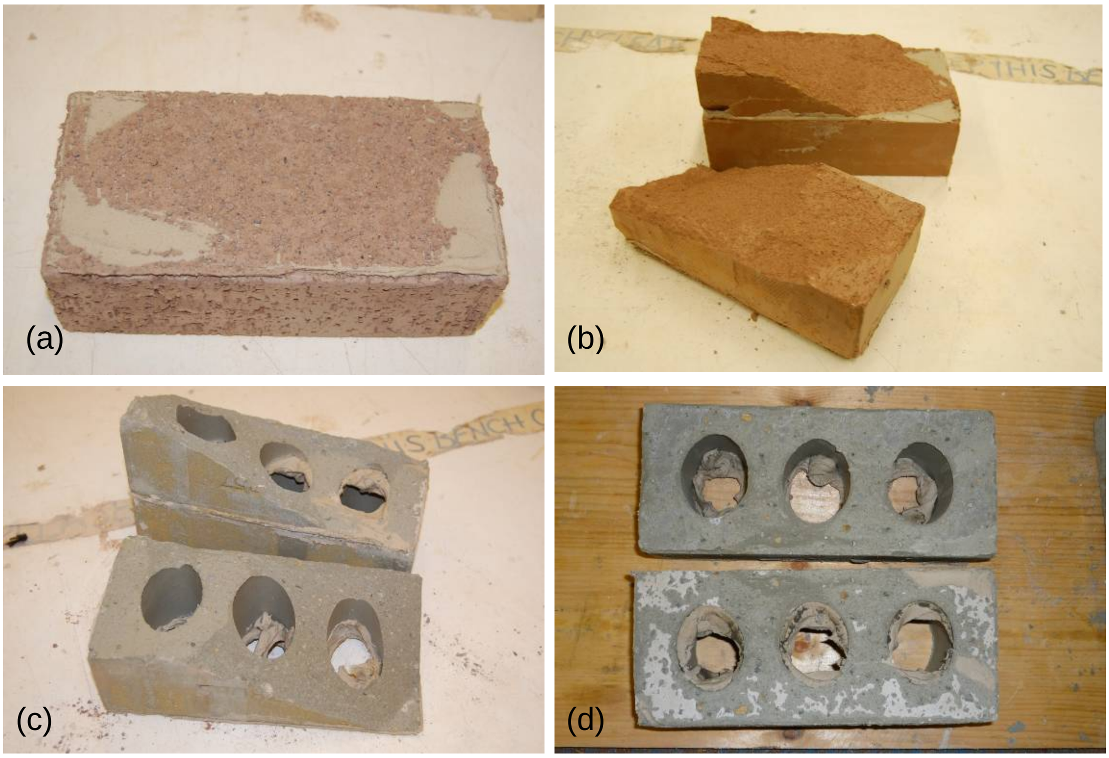

Figure 4.3 Modes of failure on testing the 3 mm thick 10 % commercial sodium silicate mortar joints using the bond wrench test method in stacks prepared using Units 2, 4 and 5 respectively (a) Units 2 delaminating onto mortar at interface, (b) failure through Units 4, (c) failure through Units 5 and (d) Units 5 delaminating onto mortar at interface

4.4.1 Composition and preparation of sodium silicate clay mortars

Sodium silicate mortars were developed for Units 2 and 5 using the respective brick clays (i.e. Soils 2 and 5). Clays were ground to a particle size of less than 0.5 mm and fine builders sand (Figure 4.4) was added to the mortars to minimise shrinkage on drying. A mixture of 1 part clay to 3 parts sand was required to minimise the shrinkage of brick clay 2 on drying and a mixture of 1 part clay to 4 parts sand to minimise shrinkage of brick clay 5 on drying (Figure 4.5). The higher sand content required for brick clay 5 was due to the higher clay content which gave rise to the higher shrinkage of the clay on drying.

Sodium silicate was added in various quantities to the clay/sand mortars developed. Sodium silicate contents of 5 %, 7.5 % and 10 % by weight were used for the brick clay 5 mortars. These contents were based on the mortar bond strengths obtained when using the commercial sodium silicate mortar to establish whether a sodium silicate content of less than 10 % would give suitable mortar bond strengths. Sodium silicate contents of 8 %, 10 % and 12 % by weight were used for brick clay 2 mortars. These contents were based on the bond strengths obtained from the brick clay 5 mortars to improve on the strength, stability and variability of mortar and bonds.

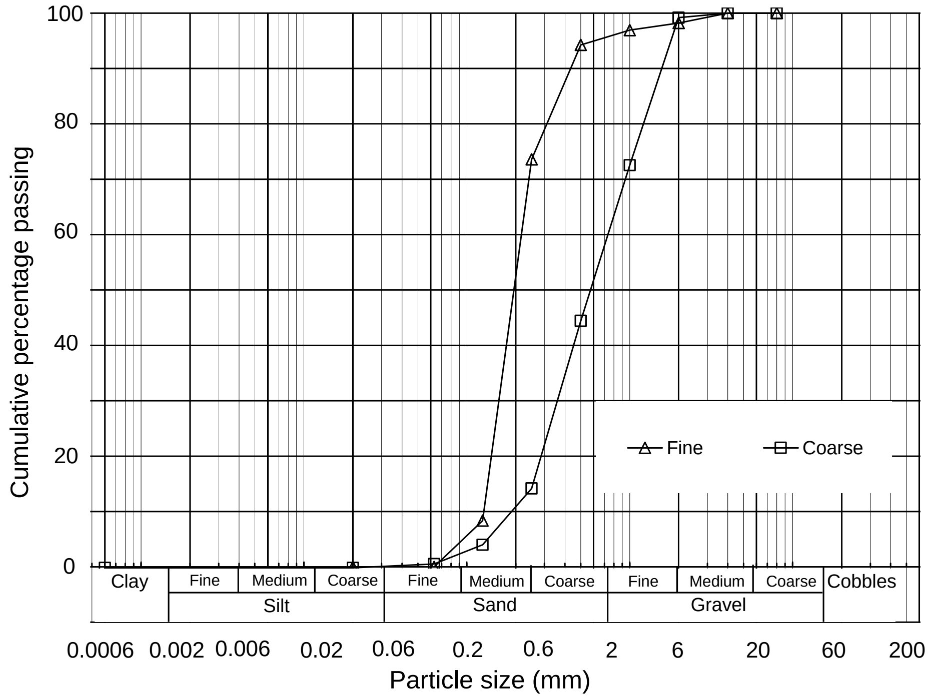

Figure 4.4 Sieve analyses of fine and coarse builder sands

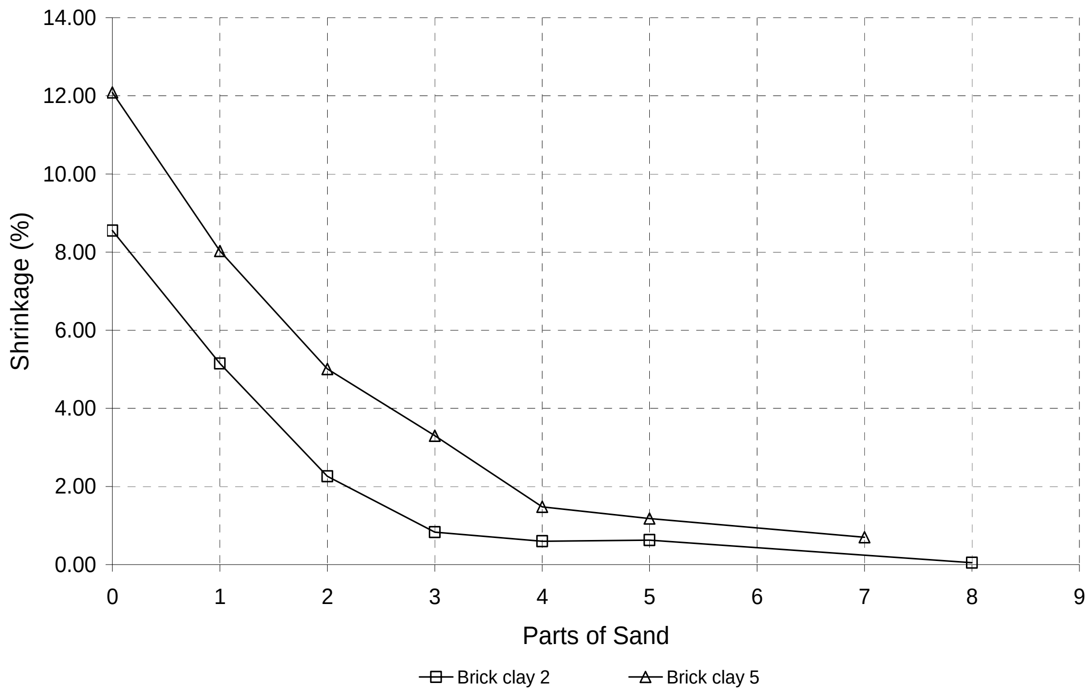

Figure 4.5 Shrinkage with sand content of brick clays 2 and 5 at the respective liquid limits of the clays

Sodium silicate powder was mixed dry into the respective mortars using a pan mixer. Water was added to give a consistency suitable for trowel application. A water content of 25 % was used in all of the brick clay 2 mixtures to eliminate the influence of moisture content on strength. The water contents of brick clay 5 mixtures were adjusted to compensate for the increase in workability imparted at the higher sodium silicate contents (26.7 % water by weight for the 5 % mixture, 21.4 % for the 7.5 % mixture and 20.9 % for the 10 % mixture).

4.4.2 Bond strengths of brick clay 5 mortars

Stacks were prepared using mortars developed from brick clay 5 containing 0%, 5 %, 7.5 % and 10 % sodium silicate. A mortar bed (approximately 3 mm thick) was laid with a trowel to prepare the stacks. Stacks were conditioned at 20 °C and 60 % - 65 % RH for 3, 7, 14, 28, 91 and 365 days respectively prior to the determination of mortar bond strengths (average of twelve determinations). Bond strengths obtained for the mortar without sodium silicate were not recorded. Only a few measurements were possible due to failure of the stacks on handling and preloading in the testing rig. This was due to the poor bond strength of the mortar (0.07 N/mm^2 which was the highest from those determined). No evidence of the mortar bonding to the brick units were observed upon failure (Figure 4.6a).

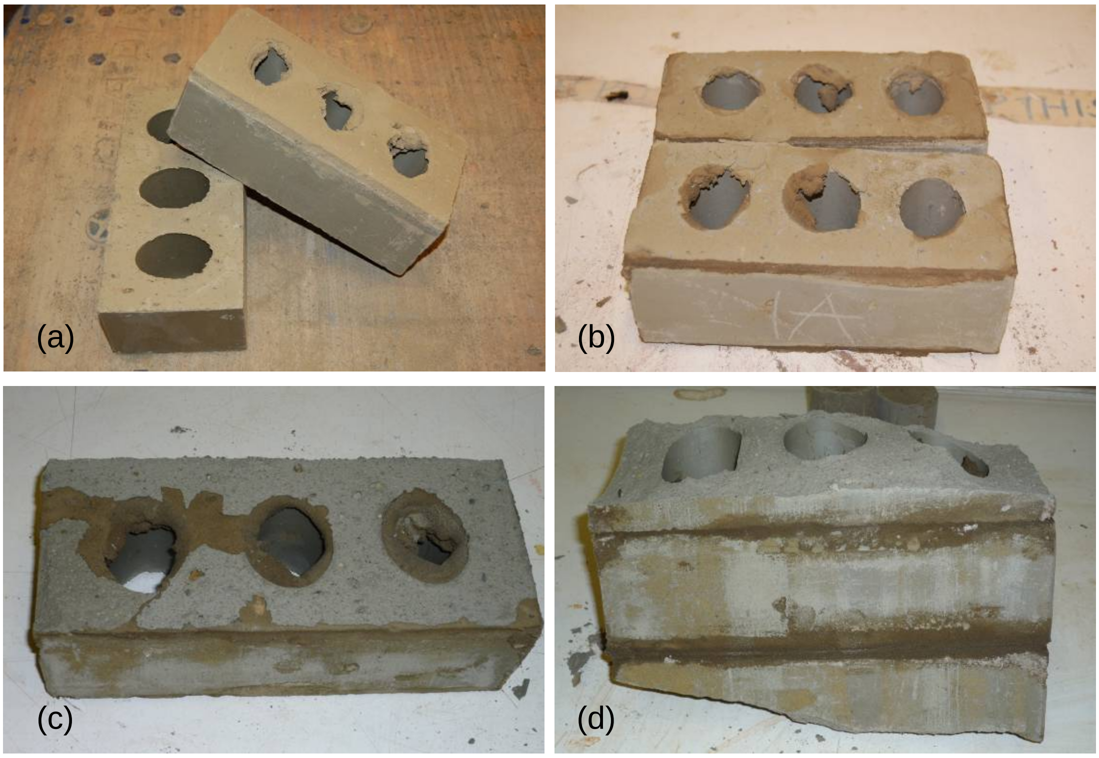

Figure 4.6 Modes of failure of the sodium silicate mortars developed using brick clay 5 - (a) 0 % sodium silicate showing interface failure (b) 5 % sodium silicate showing mortar failure (c) 7.5 % sodium silicate showing brick unit delaminating onto mortar (d) 10 % sodium silicate showing failure through brick units

Average and characteristic bond strengths of the 5 % sodium silicate mortar (minimum and maximum values of 0.08 N/mm^2 to 0.18 N/mm^2 and 0.04 N/mm^2 to 0.11 N/mm^2 respectively for the entire range of joints tested) were all substantially lower than those of the 7.5 % (range of 0.39 N/mm^2 to 0.48 N/mm^2 and 0.21 N/mm^2 to 0.37 N/mm^2 respectively) and those of the 10 % (range of

0.50 N/mm^2 to 0.58 N/mm^2 and 0.22 N/mm^2 to 0.39 N/mm^2 respectively) sodium silicate mortars (Table 4.2). Average bond strengths were almost double the characteristic bond strengths and the range of bond strengths (i.e. minimum to maximum value) within a set of measurements (i.e. twelve joints per mortar tested at the specified time intervals) was high (Table 4.2).

Table 4.2 Bond strengths of the sodium silicate mortars developed using brick clay 5 conditioned at 20 °C and 60 % – 65 % RH for various times

Age (days)	**Mortar**	**Bond Strength** (N/mm^2)			
		Average	Characteristic	Stdev	Range
3	5 %	0.11	0.06	0.04	0.13
	7.5 %	0.39	0.25	0.10	0.37
	10 %	0.53	0.33	0.12	0.33
7	5 %	0.12	0.05	0.06	0.18
	7.5 %	0.42	0.28	0.08	0.29
	10 %	0.53	0.27	0.16	0.50
14	5 %	0.10	0.04	0.04	0.13
	7.5 %	0.39	0.27	0.07	0.20
	10 %	0.50	0.22	0.20	0.58
28	5 %	0.12	0.06	0.05	0.15
	7.5 %	0.39	0.21	0.14	0.49
	10 %	0.52	0.33	0.13	0.42
91	5 %	0.18	0.11	0.04	0.14
	7.5 %	0.43	0.22	0.13	0.40
	10 %	0.58	0.39	0.11	0.32
365	5 %	0.08	0.07	0.01	0.02
	7.5 %	0.48	0.37	0.06	0.16
	10 %	0.55	0.38	0.10	0.31

Approximately 70 % of the failures for the 5 % sodium silicate joints tested occurred at the interface (i.e. de-bonding) between the mortar and brick unit (Figure 4.6a). The remaining joints failed through the mortar (Figure 4.6b). Approximately 70 % of the failures for the 7.5 % sodium silicate joints tested were through the brick units either from the bricks delaminating onto the mortar at the bond interface (Figure 4.6c) or directly through the brick units (Figure 4.6d). The remaining joints failed through the mortar. All failures for the 10 % sodium silicate mortar joints were directly through the brick units with the exception of seven joints (five where the brick delaminated onto the mortar and two where the failure was through the mortar).

Average bond strengths of each of the three sodium silicate mortars with time were not significantly different (Table 4.2). The only exception was the higher than average bond strength of the 5 % sodium silicate mortar at 91 days (Table 4.2). A statistical analysis (i.e. two tail t-test assuming unequal variance) confirms that the average bond strength at 91 days is significantly different to those measured at other times. All failures in the 5 % sodium silicate stacks tested at 91 days were through the mortar and not due to de-bonding of the mortar at the interface, which was the common failure mode at other times. It is not clear why this was the case. All 5 % sodium silicate stacks were made using the same batch of mixed mortar and brick units. It is assumed the difference was due to variation in the test procedure and that de-bonding at the interface failure was reported as mortar failure instead. A similar error was noted in other stacks which were tested by the same operator and not by the author.

Characteristic bond strengths (i.e. design bond strength) with time for all three mortars were erratic. Characteristic bond strengths of the 5 % and 10 % sodium silicate mortars steadily decreased over the first 14 days and then increased (Figure 4.7). After 91 days the characteristic bond strength of the 5 % sodium silicate mortar decreased whereas that of the 10 % sodium silicate mortar remained fairly constant. Characteristic bond strength of the 7.5 % sodium silicate mortar increased over the initial 7 days and then steadily decreased over the next 21 days. After 28 days the characteristic bond strength of the 7.5 % mortar steadily increased.

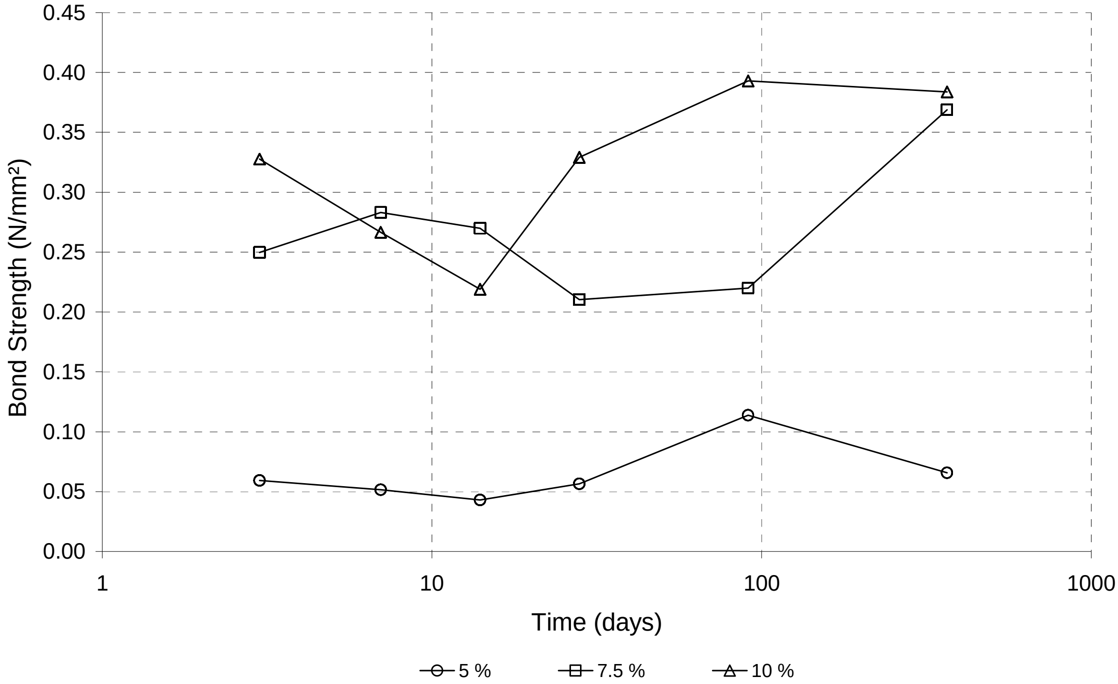

Figure 4.7 Characteristic bond strengths with time (logarithmic scale) of the 5 %, 7.5 % and 10 % sodium silicate mortars developed using brick clay 5 and conditioned at 20 °C and 60 % - 65 % RH

The failure of the characteristic bond strengths to follow the expected trend that is, gradually increasing after 3 days and then stabilising after 28 days once the mortars dried out (Figure 4.7). This was mainly due to the variability within a set of measurements namely when one or more of the twelve joints tested failed at a significantly lower value than the others (see range values Table 4.2). For example, the low characteristic bond strengths at 28 days and 91 days in comparison to that at 365 days for the 7.5 % sodium silicate mortar was due to the low measurements within each set of joints tested at these times (i.e. 0.24 N/mm^2 and 0.25 N/mm^2 respectively), which is substantially lower than the mean values (i.e. 0.39 N/mm^2 and 0.43 N/mm^2 respectively), and the high variability within each set of measurements (i.e. range of 0.49 N/mm^2 and 0.40 N/mm^2 respectively). At 365 days the lowest measurement was 0.40 N/mm^2 substantially higher than those at 28 days and 91 days and the variability (i.e. range of 0.16 N/mm^2) within the set of measurements was substantially lower.

Adding sodium silicate to the clay/sand mortar mixture improves the capacity of the mortar to bond onto the brick units and the strength of the mortar. Average and characteristic bond strengths were significantly improved and with sodium silicate contents above 7.5 % the strengths and bond strengths of the clay/sand mortar were suitable for the construction of thin walls using a thin mortar joint (i.e. 3 mm thick bed). Strengths at early ages namely three days and after long time periods for the 7.5 % and in particular the 10 % sodium silicate mortars were above the 0.2 N/mm^2 required for thin wall construction.

Average and characteristic bond strengths with time of the 5 % sodium silicate mortar were significantly lower than the 0.2 N/mm^2 required for thin wall construction. Only three of all the joints tested gave bond strengths higher than 0.2 N/mm^2. At such a low concentration there is not sufficient sodium silicate firstly to give the mortar the bond strength and secondly the strength required to resist lateral loading. This is evident form the modes of failure observed. Failures were predominantly due to the mortar de-bonding from the brick unit whereas all the remaining failures were through the mortar.

It is speculated that the sodium silicate dissolved in the moisture of the mortar is absorbed across the interface between brick and mortar and into the brick unit. On drying it forms a strong bond between the mortar and the brick units (i.e. the sodium silicate acts as an adhesive and glues the brick onto the mortar). A higher concentration than 5 % is required when using a 3 mm thick mortar bed to ensure there is sufficient sodium silicate for absorption into the brick to fuse it onto the mortar and that there is sufficient sodium silicate left within the mortar to adhere the particles together on drying and strengthen the mortar.

At a sodium silicate content of 7.5 % the characteristic bond strengths of the mortar with time were above that required for thin wall construction (i.e. strengths of all the joints tested were above the 0.2 N/mm^2 required). Characteristic bond strengths calculated, which were in some instances just above the 0.2 N/mm^2, indicate that a sodium silicate content of 7.5 % was the minimum required to ensure the 3 mm thick mortar joint is suitable for the construction of thin walls using brick units 5.

Strengths and variability in the strengths of the brick units in this loading direction (i.e. 90° to the perforations) were similar to those of the 7.5 % sodium silicate mortar and mortar bonds. Modes of failure namely, de-lamination of brick unit onto the mortar (20 %) and failure through the mortar (30 %), indicate that the strength and bond strength of the mortar were similar or higher than that of brick units 5. In addition, no correlation existed between the modes of failure and the bond strengths measured (i.e. failures directly through the brick units (50 %) were not only associated with the higher strengths measured and failures through the mortar were not only associated with lower strengths measured).

Characteristic bond strengths with time of the 10 % sodium silicate mortar were all above that required for thin wall construction and on average the strengths of the joints tested were substantially higher than 0.2 N/mm^2. Such high characteristic bond strengths and the fact that all of the failures occurred through the brick units indicate that the strength and bond strength of the mortar with a sodium silicate content of 10 % were too high for the construction of thin walls with brick units 5.

4.4.3 Bond strengths of brick clay 2 mortars

Stacks were prepared using mortars developed from brick clay 2 containing 8%, 10 % and 12 % sodium silicate. A mortar bed (approximately 3 mm thick) was laid with a trowel to prepare the stacks. Stacks were conditioned at 20 °C and 60 % - 65 % RH for 1, 3, 7, 14, 28, 92 and 410 days respectively prior to the determination of mortar bond strengths (average of twelve determinations). Some spare 10 % and 12 % sodium silicate stacks conditioned at 20 °C and 60 % - 65 % RH were tested at 1108 days (i.e. after 3 years).

Average and characteristic bond strengths after 24 hours of all the mortars were substantially lower than those at and after 3 days (Table 4.3). At 24 hours the average and characteristic bond strengths of the 8 % sodium silicate mortar (0.17 N/mm^2 and 0.10 N/mm^2 respectively) were greater than those of the 10 % (0.12 N/mm^2 and 0.06 N/mm^2 respectively) and 12 % (0.10 N/mm^2 and 0.05 N/mm^2 respectively) sodium silicate mortars. At 3 days the average and characteristic bond strengths of all the mortars were similar (0.37 N/mm^2 to 0.39 N/mm^2 and 0.25 N/mm^2 to 0.27 N/mm^2 respectively).

Table 4.3 Bond strengths of the sodium silicate mortars developed using brick clay 2 conditioned at 20 °C and 60 – 65 % RH for various times

Age (days)	**Mortar**	**Bond Strength** (N/mm^2) Average	Characteristic	Stdev	Range
1	8 %	0.17	0.10	0.04	0.12
	10 %	0.12	0.06	0.04	0.15
	12 %	0.10	0.05	0.05	0.19
3	8 %	0.37	0.27	0.06	0.22
	10 %	0.38	0.24	0.08	0.28
	12 %	0.39	0.25	0.09	0.33
7	8 %	0.40	0.23	0.10	0.31
	10 %	0.49	0.31	0.11	0.35
	12 %	0.62	0.48	0.08	0.29
14	8 %	0.45	0.34	0.07	0.23
	10 %	0.57	0.43	0.08	0.22
	12 %	0.55	0.38	0.10	0.39
28	8 %	0.42	0.29	0.08	0.24
	10 %	0.53	0.34	0.10	0.29
	12 %	0.53	0.35	0.11	0.35
92	8 %	0.53	0.29	0.15	0.52
	10 %	0.63	0.44	0.11	0.33
	12 %	0.57	0.34	0.13	0.47
410	8 %	0.47	0.30	0.10	0.32
	10 %	0.73	0.46	0.15	0.54
	12 %	0.75	0.55	0.12	0.38
1108	8 %	-	-	-	-
	10 %	0.65	0.54	0.05	0.12
	12 %	0.59	0.38	0.09	0.19

After 3 days the average and characteristic bond strengths of the 8 % sodium silicate mortar (range of 0.40 N/mm^2 to 0.53 N/mm^2 and 0.23 N/mm^2 to 0.34 N/mm^2 respectively) were lower than those of the 10 % (0.49 N/mm^2 to 0.73 N/mm^2 and 0.31 N/mm^2 to 0.46 N/mm^2 respectively) and 12 % (0.53 N/mm^2 to 0.75 N/mm^2 and 0.34 N/mm^2 to 0.55 N/mm^2 respectively) sodium silicate mortars. At 1108 days the average bond strengths and characteristic bond strengths of the 10 % sodium silicate stacks (0.65 N/mm^2 and 0.54 N/mm^2 respectively – average of five determinations) and 12 % sodium silicate stacks (0.59 N/mm^2 and 0.38 N/mm^2 respectively – average of three determinations) were similar to those at their earlier ages.

Characteristic bond strengths sharply increase after the initial 24 hours and decreased after 7 days for the 12 % sodium silicate mortar and after 14 days for the 8 % and 10 % sodium silicate mortars (Figure 4.8). After 28 days the characteristic bond strength of the 8 % and 12 % sodium silicate mortars remained constant and that of the 10 % sodium silicate mortar increased. After 91 days the strength of the 12 % sodium silicate mortar increased and those of the 10 % and 8 % sodium silicate mortars remained constant. After 410 days the characteristic strengths (i.e. at 1108 days) of the 10 % sodium silicate increased whereas that of the 12 % sodium silicate mortar once again decreased. Characteristic strengths at these later ages were of the same orders of magnitude as those calculated at earlier ages but according to the standard (BS EN 1052-5:2005) these characteristic strengths were not representative as the calculations were only based on five and three determinations respectively. A minimum of 10 measurements are required to limit variation in the calculation, however according to the characteristics of the unfired clay materials tested thus far the calculations at 1108 days were acceptable to compare to those at the earlier times (refer to Figure 4.2).

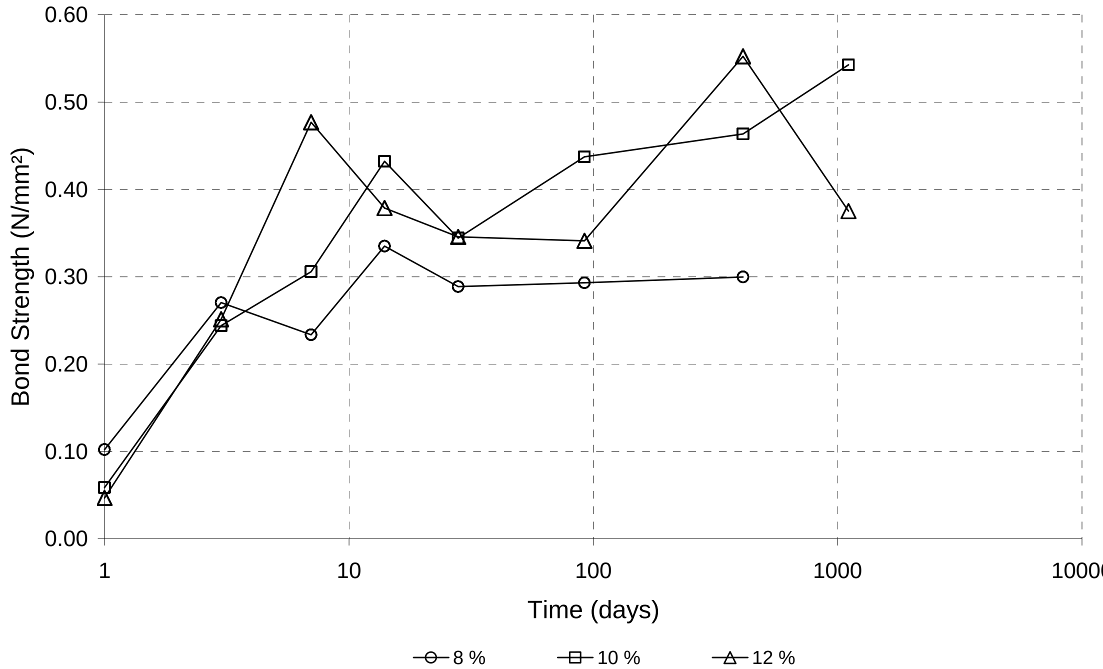

Figure 4.8 Characteristic bond strengths with time (logarithmic scale) of the 8 %, 10 % and 12 % sodium silicate mortars developed using brick clay 2 and conditioned at 22 °C and 60 % RH

All the joints tested at 24 hours for each of the three sodium silicate mortars failed directly through the mortar (Figure 4.9a). After 3 days the modes of failure for the 8 % sodium silicate mortar joints were either through the brick units (54 %) or through the mortar (46 %) whereas 97 % of the joints tested for the 10 % and 12 % sodium silicate mortars failed through the brick units and only 3 % failed through the mortar (Figure 4.9).

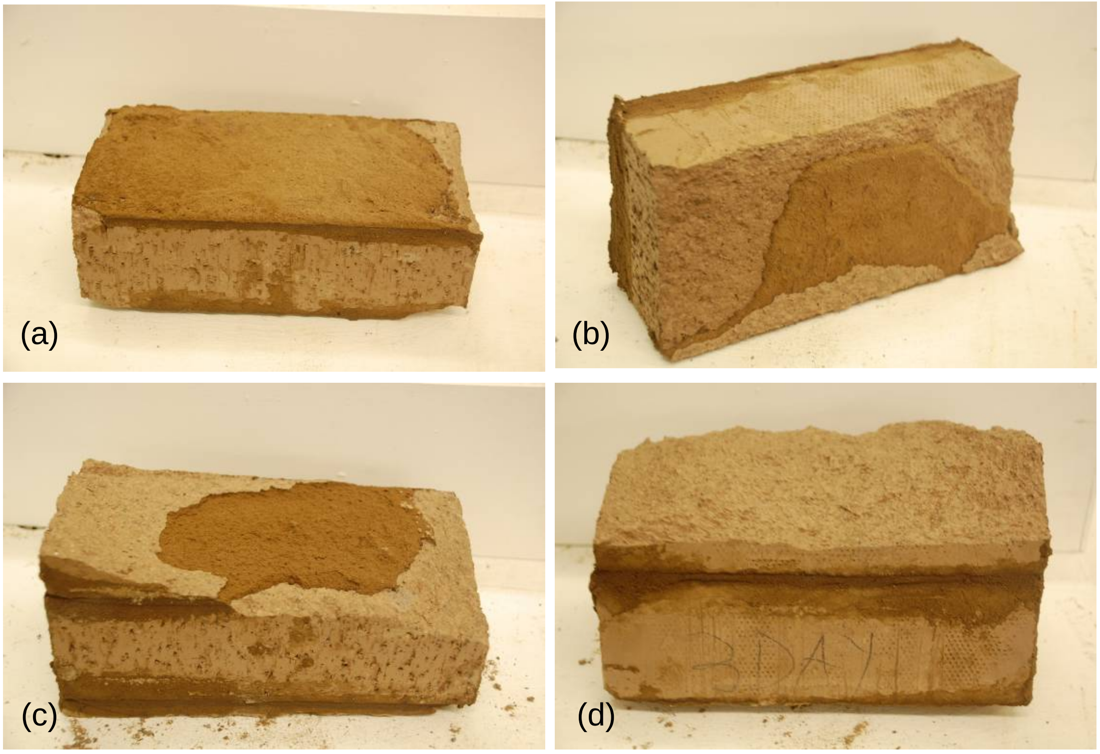

Figure 4.9 Modes of failure of the sodium silicate mortars developed using brick clay 2 - (a) shows a mortar failure typically for the joints tested at 24 hours, (b), (c) and (d) shows the failure through brick units 2 at and after 3 days

Average bond strengths of the 8 % sodium silicate mortars were similar after 1 day whereas that for the 10 % and 12 % sodium silicate mortars were similar after 3 days the only exceptions being the higher average bond strengths for the 12 % mortar at 7 days and the higher average bond strengths of the 10 % and 12 % sodium silicate mortars at 410 days. Statistically (two tail t-test assuming unequal variables there was no significant differences between the average bond strengths at these and other times.

Characteristic bond strengths calculated for the brick clay 2 mortars with time were erratic. The expected trends of an increase in strength with the hardening of the mortars and the stabilisation in strength thereafter were not followed. This was due to variability within a set of measurements and a substantially lower than average bond strength measurement within the set. For example, the lower characteristic bond strength for the 8 % mortar at 7 days compared to those at 3 days and 14 days was due to a lower than average bond strength measurement at 7 days (i.e. 0.22 N/mm^2 compared to average of 0.40 N/mm^2). The lower characteristic bond strengths of the 12 % mortar at 14 days, 28 days and 92 days compared to those at 7 days and 410 days were due to a substantially lower bond strength measurement within each set at 14 days (0.38 N/mm^2), 28 days (0.33 N/mm^2) and 92 days (0.34 N/mm^2) compared to those measured within each set at 7 days (0.47 N/mm^2) and 410 days (0.60 N/mm^2)

which gave the higher characteristic bond strengths than those calculated for the 10 % mortar at 7 days and 410 days. Similarly, the lower characteristic bond strength at 28 days compared to those at 14 days, 92 days and 410 days of the 10 % mortar was due to a lower bond strength measurement within the set at 28 days (0.34 N/mm^2 compared to 0.46 N/mm^2, 0.45 N/mm^2 and 0.41 N/mm^2 respectively).

The substantially lower characteristic bond strength calculated at 1108 days for the 12 % sodium silicate mortar could not be accounted for as above. This was due to the testing of only three joints (i.e. one stack) each of which was of gave a lower than average bond strength (i.e. similar to those measured at the earlier ages namely 14 days, 28 days and 91 days, which resulted in the low characteristic strengths values calculated).

The brick clay 2 sodium silicate mortars were all suitable for the construction of thin walls using a 3 mm thick bed. Good early strength development (i.e. after 24 hours) indicates that the mortars are suited for the laying of a few courses at a time. At and after 3 days the characteristic bond strengths of all the mortars were above the 0.2 N/mm^2 required (i.e. all the joints tested for each mortar gave strengths higher than 0.2 N/mm^2). After discarding the substantially lower than average bond strength measurements, characteristic bond strengths of the mortars either remained stable or increased with age after 14 days. The 10 % and 12 % sodium silicate mortars also gave good strength at later ages (i.e. after 3 years) indicating that the mortars remained stable over time.

After 24 hours the strength of the 8 % sodium silicate mortar was similar (or more precisely slightly lower or slightly higher) to that of the brick units as modes of failure were either through the brick units or mortar beds. The bond strengths of the 8 % mortar were significantly higher than the strengths of the mortar and brick units as no failures occurred from de-bonding of the mortar at the joint interfaces. Strengths and bond strengths of the 10 % and 12 % sodium silicate mortars were substantially higher than that of the brick units as modes of failure were directly through the brick units. A sodium silicate of 8 % is therefore sufficient for the construction of thin walls using a 3 mm thick bed.

The higher early strength development for the 8 % sodium silicate mortar (i.e. at 24 hours and 3 days) was due to the mortar drying or hardening at a faster rate than the 10 % and 12 % sodium silicate mortars. This is related to the hygroscopic nature of the sodium silicate slowing the evaporation of the water at the higher sodium silicate concentrations. The water content in the 10 % and 12 % sodium silicate mortars can be reduced to offset the slower evaporation of the water. Similar water contents were used in all the mixtures to eliminate variability such as amount and rate of water absorption into the brick units. A reduction in water content is possible due to the increase in workability of the mixtures at higher sodium silicate contents.

An increase in the sodium silicate content significantly increases the mortar bond strengths after 3 days. After discarding the bond strength measurements relating to premature failure within each set of measurements the characteristic bond strengths of the 8 % sodium silicate mortar with time were substantially lower than that of the 10 % and 12 % sodium silicate mortars. This is directly related to the higher strength development in the mortar and bond at the higher sodium silicate contents prompting failure through the brick units and not through the mortar. The difference in bond strengths between the 10 % and 12 % mortars are not as substantial as failure occurs through the brick units for both mortars.

After discarding the lower than average bond strengths measurements the characteristic bond strength of the 12 % sodium silicate mortar was significantly higher than that of the 10 % sodium silicate mortar. At higher concentrations more sodium silicate is absorbed into the brick units which strengthen the bricks adjacent to the mortar accordingly. Owing to the manner in which the brick units are clamped (Figure 4.1) and wrenched (i.e. twisting of the top unit) the brick units tend to fail in the region directly above and below the mortar (Figure 4.9b, c and d). An increase in strength in these areas will therefore give rise to and increase in bond strengths.

4.5 Influence of coarseness and sand content on mortars

An investigation was done using the clay mortars developed from brick clays 2 and 5 to determine the influence of the sand and clay on the mortar bond strengths when using the minimum sodium silicate content of approximately 8 % to ascertain if it is sufficient to compensate for variations in the mortar such as those introduced on-site.

4.5.1 Sand coarseness and sand content

The influence of sand coarseness and sand content on the bond strengths were investigated using a 7.5 % sodium silicate content and mortars developed from the finely ground brick clay 5. Sand coarseness was investigated using sand containing flat angular shape particles (Figure 4.4) mixed using the same ratio as that for the fine builders sand (i.e. 1 part clay to 4 parts sand). Sand content was investigated by doubling the quantity of fine builder sand in the mixture (i.e. using a ratio of 1 part clay to 8 parts sand). Stacks (four for each of the mortars) were prepared using a 3 mm thick mortar bed applied with a trowel and conditioned for 28 days at 20°C and 60 % - 65 % RH prior to testing. The water content of the coarse sand mixture was similar to that used for the fine builders sand mixture (21 %). The water content of the lean (1:8) mixture was substantially lower than the standard (1:4) mixture to compensate for the increased workability arising from the higher sand content (16 %).

At 28 days the average and characteristic bond strengths (average of twelve determinations – Table 4.4) of the 1:4 coarse sand mortar (0.39 N/mm^2 and 0.27 N/mm^2 respectively) and the 1:8 lean fine sand mortar (0.45 N/mm^2 0.27 N/mm^2 respectively) were higher than that of the 1:4 standard fine sand mortar (0.49 N/mm^2 and 0.21 N/mm^2 respectively). The modes of failures were similar for each mortar. Failures either occurred directly through the brick unit (Figure 4.6d) or at the interface from the de-lamination of the brick onto the mortar (Figure 4.6c).

Sand content, coarseness and shape of the sand particles do not influence the bond strength of the 7.5 % sodium silicate mortar developed from brick clay 5. This should apply for all clay/sand mortars with a sodium silicate content of 8 % or higher provided that there is sufficient clay and the particle size is not larger than the thickness of the mortar joint. A certain percentage of clay is needed to bind the inert aggregates and prevent excessive bleeding which in effect would reduce the amount of sodium silicate available and decrease strength and bond strength of the mortar. The amount of clay also controls the absorption of solution into the brick units and must be sufficient to ensure enough sodium silicate solution remains within the mortar to give good strength development and is absorbed into the brick to give good bond strengths on drying. The particle size of the sand should be less or equal to 2 mm for the 3 mm mortar joint to maximise the bonding surface area between the mortar and brick unit and prevent any weak spots from which failure will propagate.

Table 4.4 Bond strengths of the coarse and lean 7.5 % sodium silicate brick clay 5 mortars conditioned at 20 °C and 60 % - 65 % RH for 28 days

Mortar	**Bond Strength** (N/mm^2)			
	Average	Characteristic	Stdev	Range
1 : 4 fine sand	0.39	0.21	0.14	0.49
1 : 4 coarse sand	0.45	0.27	0.12	0.38
1 : 8 fine sand	0.49	0.27	1.16	0.49

4.5.2 Clay coarseness

Coarseness of the clay on the bond strength was investigate using a mortar containing 8 % sodium silicate, 1 part brick clay 2 in its un-ground state (i.e. in it's factory supplied form) and 3 parts fine builders sand (i.e. the same ratio as that used for the finely ground brick clay 2 mortars). Four stacks were prepared using a 3 mm thick mortar bed applied with a trowel. The water content of the coarse clay mixture (27 %) was higher than that of the fine clay mixture (25 %). Stacks were conditioned at 20°C and 60 % - 65 % RH prior to testing. The bond strengths of the joints in two of the stacks were measured after 3 days and the remaining two after 7 days.

At 3 days and 7 days the average bond strengths of the coarse clay mortar (0.13 N/mm^2 and 0.20 N/mm^2 respectively – average of six determinations) were substantially lower than those of the fine clay mortar (0.37 N/mm^2 and 0.40 N/mm^2 respectively – average of twelve determinations) (Table 4.5). At 3 days the characteristic bond strengths of the coarse clay mortar was very low in comparison to that of the fine clay mortar (0.05 N/mm^2 compared to 0.27 N/mm^2 respectively) (Table 4.5). At 7 days there was a significant difference in the characteristic bond strengths between the two mortars (0.15 N/mm^2 and 0.23 N/mm^2 respectively). At 3 days the modes of failure for both the coarse and fine clay mortars were through the mortar. At 7 days the coarse clay joints failed through the mortar whereas the fine clay joints failed either through the brick units or through the mortar.

The substantially lower bond strengths and comparison of the failure modes at 3 days and 7 days indicates that the strength development in the coarse clay mortar was substantially lower than that in the fine clay mortar (i.e. mortar failures at 3 days for the fine clay mortar ranged from 0.26 N/mm^2 to 0.48 N/mm^2 compared to 0.16 N/mm^2 to 0.22 N/mm^2 for the coarse clay mortar and at 7 days the fine clay mortar gave failures through the brick units whereas the coarse clay gave failures only through the mortar).

Table 4.5 Bond strengths of coarse and fine 8 % sodium silicate brick clay 2 mortars conditioned at 20 °C and 60 % - 65 % RH for 3 and 7 days

Age (days)	**Mortar**	**Bond Strength** (N/mm^2)			
		Average	Characteristic	Stdev	Range
3	1 : 3 fine clay	0.37	0.27	0.06	0.22
	1 : 3 coarse clay	0.13	0.05	0.05	0.13
7	1 : 3 fine clay	0.40	0.23	0.10	0.31
	1 : 3 coarse clay	0.20	0.15	0.03	0.06

A sodium silicate content of 8 % is too low to give the desired strength development within coarse clay mortars. The mortar contained insufficient fine material to slow the absorption of the sodium silicate solution into the brick units. After absorption the concentration of sodium silicate remaining in the mortar is too low to ensure good strength development within the mortar and give characteristic strengths greater than the 0.2 N/mm^2 required. Absorption of the sodium silicate solution into the brick units did allow for good bond formation between the brick units and coarse clay mortar. Higher sodium silicate contents are needed in the coarse clay mortar to ensure sufficient sodium silicate remains in the 3 mm mortar joint after absorption into the brick units to achieve the strengths required for thin wall construction.

4.6 Mortar application methods

Applying the mortar by dipping the brick units into sodium silicate clay mortars or using a special scoop (Figure 4.10) rather than a trowel to apply the sodium silicate mortars was investigated. Applying the mortar using a scoop or dipping of the masonry units into mortar is more cost effective. Such application methods are less time consuming and generate thinner joints reducing mortar usage. A mortar with a much lower viscosity than that used in trowel applications is required to ensure dipped surfaces are coated and that the mortar easily flows through the openings in the scoop once it is inverted and drawn over the masonry units (Figure 4.10).

Figure 4.10 Application of thin mortar bed using special scoop (Tarmac, 2011)

Dipping of the brick units was investigated using the 8 % sodium silicate mortar developed from brick clay 2 consisting of 1 part finely ground clay and 3 parts fine builders sand. Stacks consisting of three mortar joints were prepared by dipping one side of the brick unit into a low viscosity mortar containing 32 % water by weight and then placing the dipped face onto the un-dipped face of the base brick unit. Stacks were conditioned at 20°C and 60 % - 65 % RH prior to testing. Mortar bond strengths were not determined at 1 day and 3 days. These mortar joints were wet and failed during the handling of the stacks. Stacks were left for testing at later ages. Mortar bond strengths were determined at 7 days, 14 days, 28 days, 35 days, 91 days and 1127 days (i.e. after 3 years).

Average and characteristic bond strengths at 7 days (0.30 N/mm^2 and 0.18 N/mm^2 respectively) were similar to those at 14 days (Table 4.6). At 28 days and 35 days the average (0.48 N/mm^2 and 0.43 N/mm^2 respectively) and the characteristic bond strengths (0.26 N/mm^2 and 0.27 N/mm^2 respectively) were significantly higher than those at 7 days and 14 days. At 91 days the average bond strength (0.48 N/mm^2) was similar to those at 28 days and 35 days whereas the characteristic bond strength (0.19 N/mm^2) was significantly lower and similar to those at 7 days and 14 days. At 1127 days the average bond strength was similar to those at 7 and 14 days (0.33 N/mm^2) whereas the characteristic bond strength was significantly lower than those at the earlier ages (0.11 N/mm^2).

Table 4.6 Bond strengths of the dipped 8% sodium silicate brick clay 2 mortars conditioned at 20 °C and 60 % - 65 % RH for various times

Age	**Bond Strength** (N/mm^2)			
(days)	Average	Characteristic	Stdev	Range
7	0.30	0.18	0.08	0.26
14	0.30	0.19	0.08	0.19
28	0.48	0.26	0.16	0.56
35	0.43	0.27	0.10	0.28
91	0.48	0.19	0.20	0.62
1127	0.33	0.11	0.13	0.38

Approximately 82 % of all the joints tested with time failed through the mortar whereas the remaining failures were through the brick units (Figure 4.11). At 7 days three of the eighteen joints tested failed through the brick units, at 14 days one of the twelve joints, at 28 days four of the fifteen joints, at 35 days three of the nine joints, at 91 days one of the eleven joints and at 1127 days none of the twelve joints.

Characteristic bond strengths with time for the dipped 8 % sodium silicate mortar slightly increased after 7 days (Figure 4.12). After 14 days the characteristic strength increased at a faster rate. Characteristic strength remained constant after 28 days and decreased after 35 days. Higher characteristic strengths were expected at 7 days and 14 days. Strengths at 14 days in particular were expected to be similar to that at 28 days. Strengths at 91 days were expected to be similar to that at 28 days and 35 days. The low characteristic bond strengths were due to the lower than average bond strength measurements within each set (0.17 N/mm^2 compared to 0.30 N/mm^2 at 7 days, 0.20 N/mm^2 compared to 0.30 N/mm^2 at 14 days, 0.25 N/mm^2 compared to 0.48 N/mm^2 at 91 days and in particular 0.10 N/mm^2, 0.13 N/mm^2 and 0.19 N/mm^2 compared to 0.33 N/mm^2 at 1127 days). A statistical analysis between the means (two tail t-test assuming unequal variance) indicates that there are no significant differences between the average bond strengths at 1127 days and those at earlier ages, for example, at 35 days and 91 days. This implies that the characteristic bond strengths calculated at each age are comparable and representative.

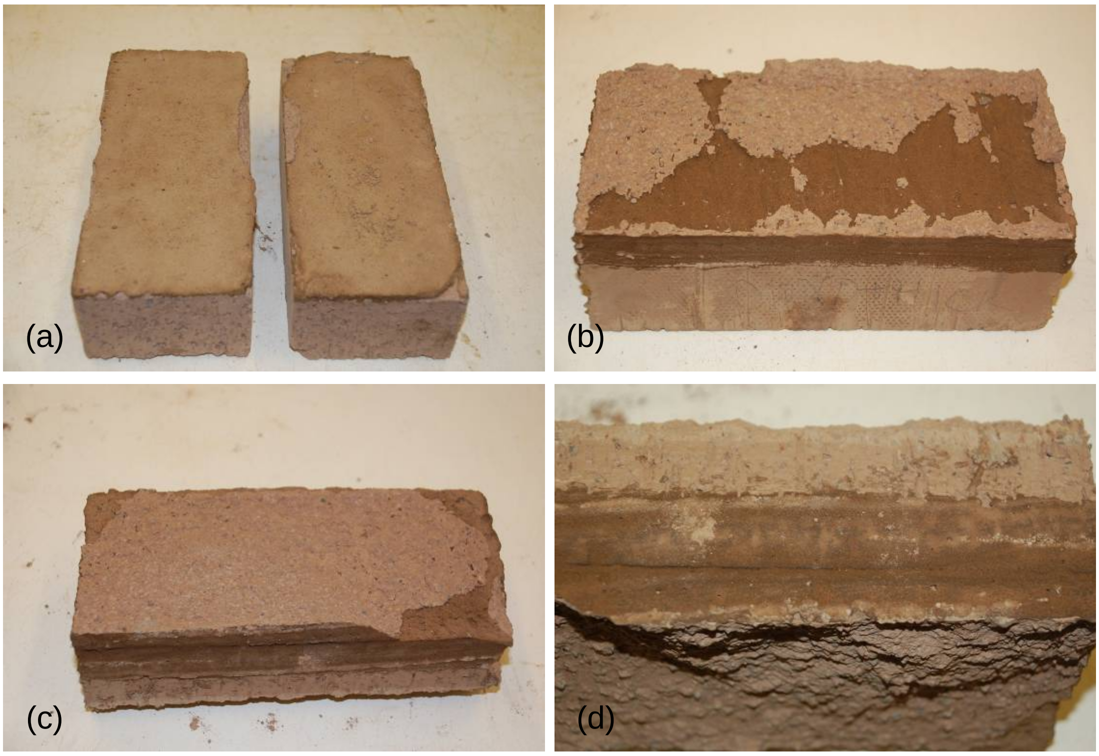

Figure 4.11 Modes of failure of the dipped 8 % sodium silicate mortars developed using finely ground brick clay 2 - (a) mortar failure typically for the joints at 24 hours, 3 days and 1127 days, (b) brick failure onto mortar seen at 7 days, (c) and (d) failure through brick units at 7 days and later ages

A dipping mortar at 8 % sodium silicate content was not suitable for the construction of thin walls. Characteristic bond strengths for the mortar were lower than the 0.20 N/mm^2 required for thin wall construction primarily at early ages (i.e. 3 days, 7 days and 14 days) but also at later ages (i.e. 91 days). On average the bond strengths measured were significantly higher than 0.20 N/mm^2 and only two of the joints tested failed at strengths less than 0.20 N/mm^2 (i.e. at 7 days 0.17 N/mm^2 and 0.18 N/mm^2). Variability in the bond strength measurements associated with the lower than average measurements (i.e. less than 0.25 N/mm^2) were responsible for the inferior characteristic bond strengths calculated.

Characteristic bond strengths of the 8 % dipping mortar were significantly lower than those of the 8 % trowel mortar with time (Figure 4.12). At 28 days and 35 days characteristic strengths were comparable but this was due to a lower than average bond strength measured at both 28 days and 91 days for the trowel mortar. On average, strengths of the dipped joints were substantially lower than those of the trowel joints and the 91 day characteristic strength was below the target of 0.2 N/mm^2. Average bond strengths of the dipped mortar at 7 days, 14 days and 91 days were 0.30 N/mm^2, 0.30 N/mm^2 and 0.48 N/mm^2 respectively and those for the trowel mortar were 0.40 N/mm^2, 0.45 N/mm^2 and 0.53 N/mm^2

respectively. At 28 days the average bond strengths of the dipped mortar were higher than that of the trowel mortar (0.48 N/mm^2 and 0.42 N/mm^2 respectively) but the characteristic strength calculated at 28 days for the dipped mortar was lower than that calculated for the trowel mortar, which suggests the dipped mortar joints were more variable and prone to giving lower strengths than the trowel mortar.

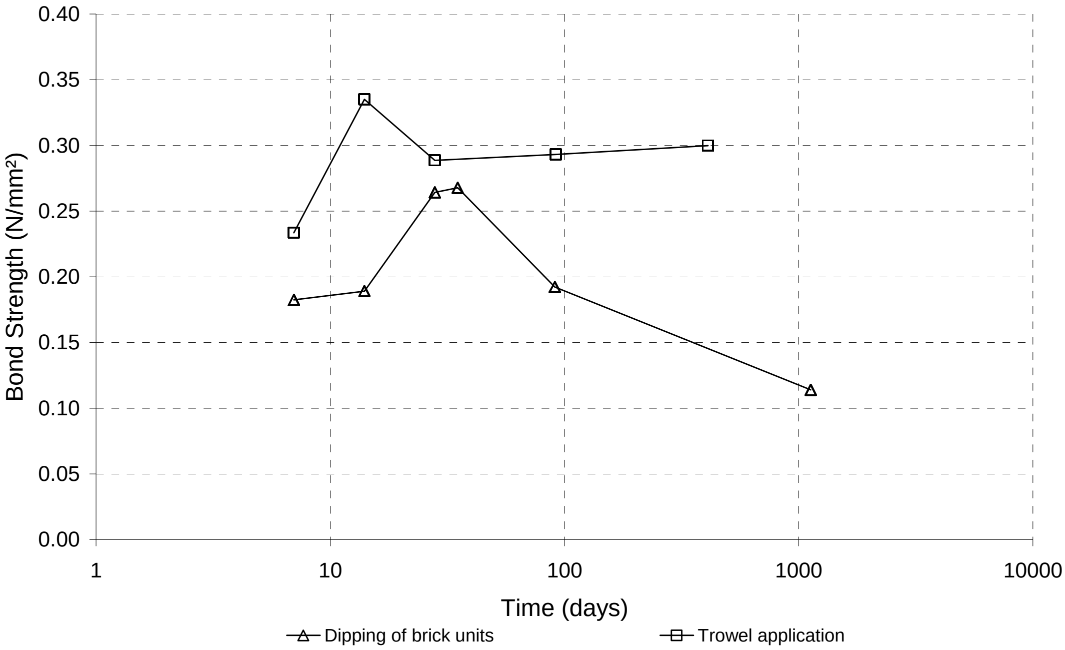

Figure 4.12 Mortar bond strengths of the dipped and trowel applied 8 % sodium silicate brick clay 2 mortars with age

On comparison of the modes of failure it is evident that the dipped mortar was of a lower strength than the trowel mortar. Approximately 50 % of the failures in the trowel mortar were due to failure of the mortar the remaining 50 % were due to failure through the brick units whereas approximately 82 % of the failures for the dipped mortar were due to mortar failure and only 8 % due to brick failure. The variability in strengths and in particular the lower strengths of the dipped joints were due to the thinner joints obtained (i.e. 1mm to 2 mm as opposed to the 3 mm required) and the method of application. At early ages, typically at 3 days where bonds broke during the handling of the specimens, and at 7 days and 14 days the lower mortar strengths of the dipping mortar was also due to the wetter mortar resulting from the higher water content of the dipped mortar.

The thin joints were due to the high water content of the dipping mortar. At 32 % water content the dipping mortar was not stiff enough to withstand the weights of the bricks. After dipping a layer of approximately 3 mm thick coats the surface of the brick but on laying the weight of the brick compresses the mortar forming the 1 mm to 2 mm joint. Such thin joints in effect reduce the amount of sodium silicate available to strengthen the mortar (i.e. after absorption into the brick units the amount of sodium silicate solution remaining in a 1 mm to 2 mm joint is significantly less than that in a 3 mm joint), and also fail to compensate for irregularities on the brick surfaces, poor tolerances of the brick units and inert particles within the mortar greater than 2 mm in size. Dipping not only fails to ensure a 3 mm thick joint but also does not ensure a layer of mortar which entirely coats the surface of the brick. Applying the mortar with a trowel not only ensures a 3 mm thick bed but also ensures the mortar coats the entire surface of the brick.

The suitability of using mortars with lower water contents for dipping and applying the dipping mortars with the special scoop was investigated. Applying the mortar using the tool aims to give a 2mm thin joint once compressed by the weight of the brick (Figure 4.13a). A mortar of low viscosity is required to give the correct rate of flow through the teeth of the scoop so that sufficient mortar is available to coat the surface of the brick. Stacks were prepared using the 8 % sodium silicate brick clay 2 mortars. Mortars with a water content of 32 % and 28 % were applied using the dipping and special scoop methods (2 mm joints) whereas a mortar with a 25 % water content was applied using a trowel (3 mm joints). Stacks were conditioned at 22 °C prior to testing at 7 days. The relative humidity was not maintained at 60 % owing to problems with the humidifier. This necessitated testing of complete series to accurately compare bond strengths. Relative humidity varied from 45 % to 60 % during conditioning.

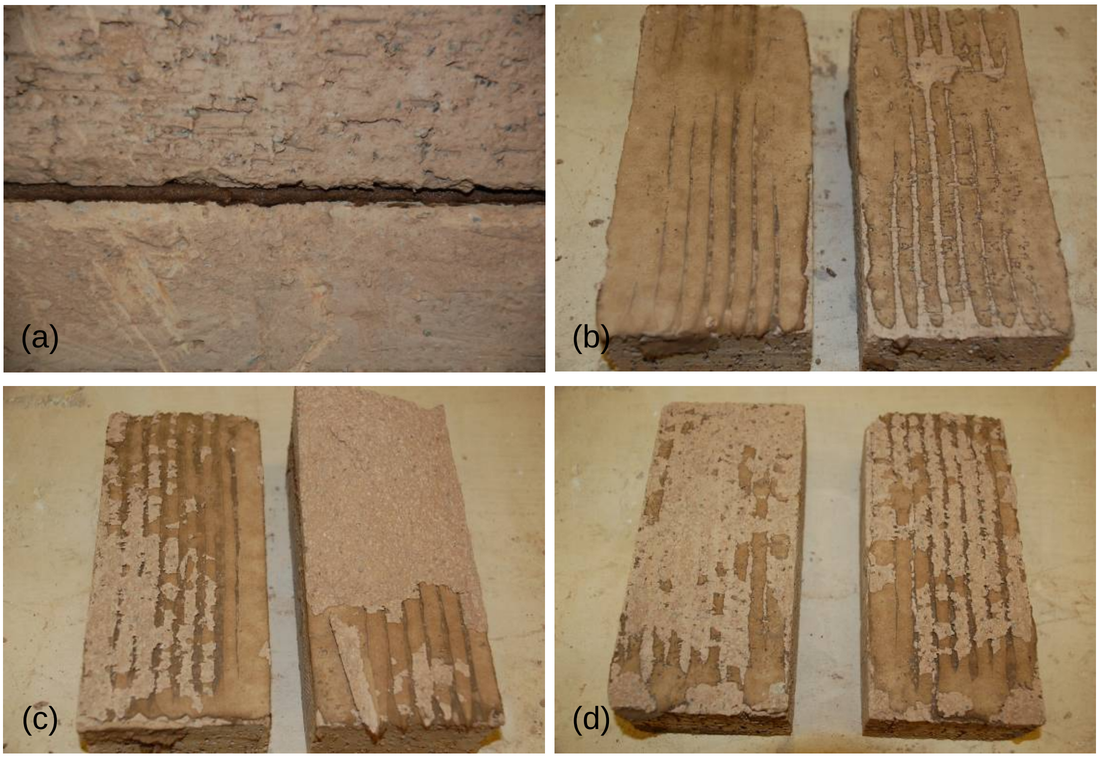

Figure 4.13 Modes of failure of the 8 % sodium silicate brick clay 2 mortars that were applied using the special scoop at 7 days - (a) 2 mm thin-joint mortar (b) mortar failure (c) and (d) failure through brick units

Average and characteristic bond strengths of the dipped and special applied mortars at 32 % water contents (average of twelve and six determinations respectively) were significantly lower than those of the dipped and scoop applied mortars at 28 % water contents (average of nine determinations), which were comparable to those of the trowel applied mortar at 25 % water content (average of nine determinations) (Table 4.7). Strengths of the joints tested for mortars at 32 % water contents applied using the dipping and special scoop methods ranged from 0.16 N/mm^2 to 0.50 N/mm^2 and 0.20 N/mm^2 to 0.39 N/mm^2 respectively. Strengths of the joints tested for mortars at 28 % water contents applied using the dipping and special scoop methods ranged from 0.27

N/mm^2 to 0.49 N/mm^2 and 0.25 N/mm^2 and 0.47 N/mm^2 respectively. Strengths of the joints for the trowel mortar ranged from (i.e. from 0.29 N/mm^2 to 0.53 N/mm^2).

Table 4.7 Bond strengths of 8% sodium silicate brick clay 2 mortars applied by trowel, dipping and special scoop prior to conditioning at 20 °C and varying RH (45 % to 60 %) for 7 days

Mortar	**Bond Strength** (N/mm^2)			
	Average	Characteristic	Stdev	Range
25 % trowel	0.40	0.26	0.08	0.24
32 % dipping	0.31	0.16	0.10	0.33
32 % tool	0.24	0.17	0.04	0.09
28 % dipping	0.35	0.24	0.07	0.28
28 % trowel	0.37	0.24	0.07	0.23

All joints tested for the mortars at 32 % water content failed through the mortar (Figure 4.13b) whereas those tested for the mortars at 28 % water content failed through the brick units (Figure 4.13c and d) with the exception of two joints for each set which failed through the mortar. Modes of failure for the mortars at 25 % water content were either through the mortar or through the brick units.

The 8 % sodium silicate mortars at 28 % water contents applied using the dipping and special scoop methods were suitable for the construction of thin walls (i.e. characteristic strengths calculated for both application methods were 0.24 N/mm^2). At 32 % water contents both application methods were not suitable for the construction of thin walls. The characteristic strengths of the dipped and scoop applied mortars were lower than 0.2 N/mm^2 (0.16 N/mm^2 and 0.17 N/mm^2 respectively). The poor strengths were due to thin joints, namely less than 2 mm thick, which cannot compensate for irregularities and tolerances on the surfaces of the brick units resulting in premature failure through the mortar. Mortars at 28 % water contents were stiff enough to resist the weight of the bricks and 2 mm to 3 mm thick joints were obtained giving bond strengths comparable to those of the 3 mm thick trowel joints.

Application of mortars at 28 % water content was difficult and time consuming. A good coating covering the entire surface of the brick was only obtained with two or more dips. At 32 % water content it was easier to dip the brick and only one dip was required to coat the surface of the brick. At 28 % water content the mortar flowed through the teeth of the scoop at less than half the rate than that at 32 % water content and substantially increased the dragging time required to ensure sufficient mortar was deposited on the brick surface.

A mortar of much lower viscosity than that of a trowel mortar is required to ensure the mortar sticks to the brick and adequately coats the surface of the brick when dipped or flows through the teeth of the scoop when dragged over the surface of the brick units to give sufficient mortar to cover the entire surface after compression from the weight of the brick. A stiffer mixture which hardens quicker giving the early strengths required and resists compression from the weights of the brick units is too sticky and difficult to apply and is more prone to give layers that do not entirely coat the surface of the brick. A mortar of low viscosity with sodium silicate contents greater than 8 % is required to give good characteristic bond strengths at early and later ages, and compensate for the margin of error associated with the thinner joints.

A rudimentary investigation with the left over brick 2 units was done to assess the suitability of using a low viscosity 12 % sodium silicate mortar for dipping and scoop application. Stacks were prepared using the dipping method and the mortars developed from brick clay 2 (one stack each for the mortar with 32 % water content and that with 36 % water content (i.e. three joints for each mortar). A mortar joint of 1mm to 2mm thick was obtained with each mortar. Stacks were conditioned for 3 days at 22 °C and 60 % RH prior to testing.

At 3 days the average bond strength for the mortar at 32 % water content (0.56 N/mm^2 - 0.70 N/mm^2, 0.52 N/mm^2 and 0.46 N/mm^2 for the respective joints) was substantially lower than that for the mortar at 36 % water content (0.80 N/mm^2 - 0.53 N/mm^2, 0.95 N/mm^2 and 0.90 N/mm^2 for the respective joints). Modes of failure were all through the brick units. Strengths and bond strengths of the mortars

At 12 % sodium silicate contents the mortars with viscosities required for dipping (approximately 36 % water content i.e. similar to the consistency of thick paint) and scoop application (approximately 30 % water content i.e. similar to the consistency of gunite/shotcrete) were suitable for the construction of thin walls (i.e. after 3 days bond strengths of the joints were substantially higher than the 0.2 N/mm^2 required). At 12 % sufficient sodium silicate solution is available for absorption into the brick units to develop good bonding and strengthen the mortar to ensure the strengths of the bond and mortar overcome the effects of surface irregularities, poor tolerances and inert particle sizes on thin joints. At the lower viscosity (paint consistency) the mortar is runny and more suited to dipping than the stiffer (gunite consistency) mortar, which is suited for use with the special scoop. A good coating is obtained on the brick surface on dipping into the runny mortar. A thinner joint forms and absorption of the moisture into the brick unit is faster allowing the joints to dry faster and develop the higher early age strengths.

4.7 General discussion

Average bond strengths with time for the 8 % and 7.5 % sodium silicate mortars developed from brick clay 2 and brick clay 5 were comparable as well as those for the 10 % sodium silicate mortars developed from the respective brick clays (Figure 4.14). The higher flexural strengths of the brick clay 5 units were offset by the perforations in the brick units, which reduces the strength of the brick units in the direction of wrenching and reduces the surface area available for bonding of the mortars. There is also wastage of the mortar which drops down the perforations.

Strengths and bond strengths of the mortars were similar at 8 % and 10 % sodium silicate contents. A significantly higher amount of failures at the interface from the brick units 5 delaminating onto the mortar was observed than with brick units 2. This was due to better fusion between the brick clay 2 mortars and their respective brick units. This may be due to unit 5 having a higher clay content which may limit its permeability (i.e. ability to absorb sodium silicate across the interface). Absorption of the sodium silicate solutions into brick units 2 was better giving the bricks higher strengths at the joint interfaces than those obtained at the joint interfaces of brick units 5.

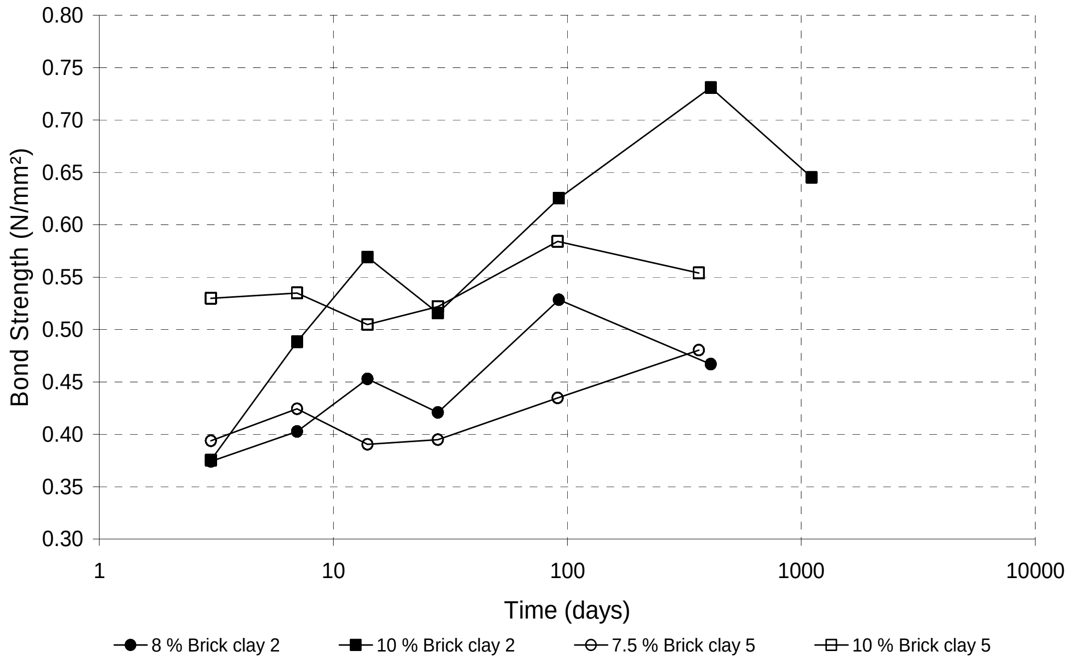

Figure 4.14 Average bond strengths with time (logarithmic scale) of the 8 % and 10 % sodium silicate mortars developed from brick clays 2 and 5

A cost and embodied carbon analysis for standard cement mortars and unfired clay mortars at different sodium silicate concentrations for different joint thicknesses was done. A standard 10 mm thick cement mortar joint of was compared to 10 mm and 3 mm thick sodium silicate unfired clay mortar joints.

At 10 mm thick the cement mortar joints are of a substantially lower cost than those of the sodium silicate unfired clay mortar joints but of a substantially higher embodied carbon (Table 4.8 and Figure 4.15). A substantial reduction in cost and embodied carbon for the sodium silicate mortars is obtained with the use of thin joints (i.e. 3 mm). For example, a 3 mm thick unfired clay mortar joint containing 10 % sodium silicate costs 6 pence/metre and contains 0.04 kg.CO_2/metre (i.e. similar to the cost of the standard 10 mm thick cement mortar joint but substantially lower embodied carbon – 0.04 kg.CO_2/metre compared to 0.4 kg.CO_2/metre) whereas a 10 mm thick joint costs 20 pence/metre and contains 0.12 kg.CO_2/metre (Table 4.8).

Such reductions in cost and embodied carbon are also possible with a substantial decrease in sodium silicate content (i.e. 5 %) but this is not desirable as a sodium silicate content of a minimum of 8 % is required to achieve the required bond strengths (Table 4.8). Sodium silicate contents of 10 % and 12 % are better as they give more room for error and safeguard against inconsistencies in the manufacture of the masonry units and mortars and those encountered during the construction of walls on-site. Owing to the improvement in properties and robustness of the thin unfired clay mortar joints the low increase in cost and embodied carbon of the mortar from 8 % to 12 % sodium silicate is insignificant.

Table 4.8 Comparison of cost (pence per meter of mortar joint) and embodied energy (kg.CO_2 per meter length of mortar joint) for cement mortar joints and sodium silicate unfired clay mortar joints (NaS) at 10 mm and 3 mm thicknesses

Mortar joints	**Cost** (p/m)	**Carbon** (kg.CO_2/m)
Cement – 10 mm	6	0.4
10 % NaS – 10 mm	20	0.12
5 % NaS – 10 mm	10	0.06
12 % NaS – 3 mm	7.2	0.05
10 % NaS – 3 mm	6	0.04
8 % NaS – 3 mm	4.8	0.03
5 % NaS – 3 mm	3	0.02

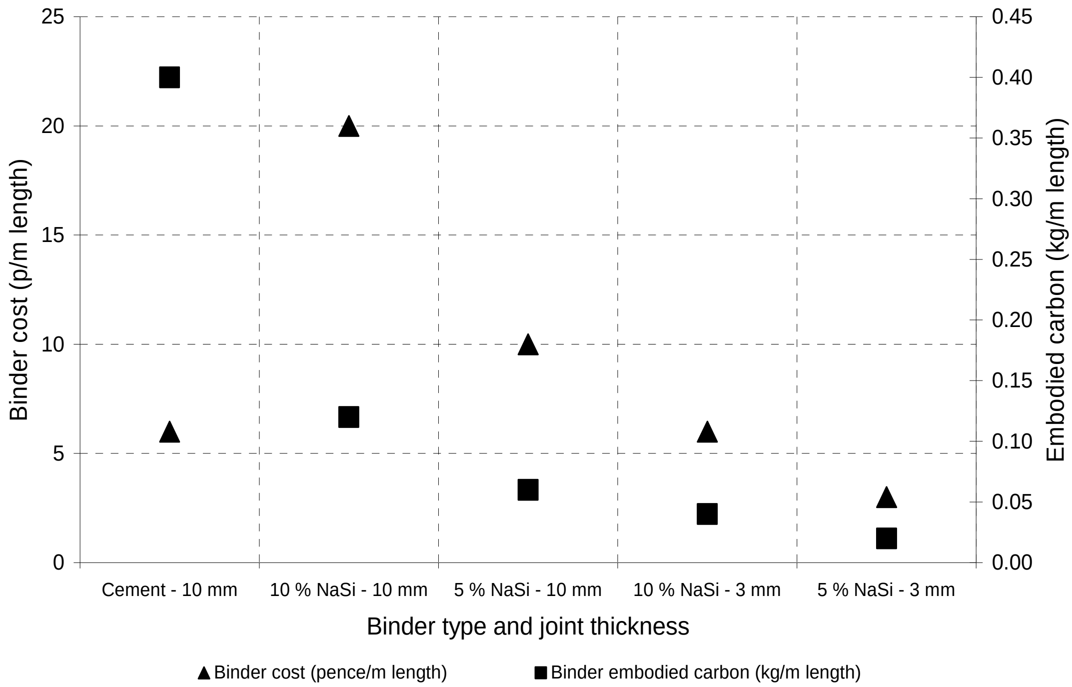

Figure 4.15 Cost (pence per metre) and embodied carbon (kg.CO_2 per metre) of standard cement and 5 % and 10 % sodium silicate unfired clay mortars at 3 mm and 10 mm joint thicknesses

Variability of the bond strengths determined for the joints within each set of stacks tested for the 8 % sodium silicate mortars was due to variability in the strength of the mortar and to some extent the variability in strength of the brick units. Modes of failure were either through the mortar or the brick units. The lower than average bond strength measurements, which were responsible for the erratic characteristic bond strengths calculated with time, were due to premature failures through the mortar. Variability in bond strengths for the 10 % and 12 % sodium silicate mortars were only due to the variation in strength of the brick units. Modes of failure were only through the brick units. The lower than average bond strength measurements giving the low characteristic bond strengths were due to the premature failure of the brick units.

The premature failure in the brick unit was not due to the variability in flexural strength of the brick unit. Compressive and flexural strengths of the brick units are fairly consistent and failure through brick units should therefore give more consistent characteristic bond strengths with time. This was not the case, for example, at ages after 3 days the 12 % sodium silicate mortar developed using brick clay 2 gave substantially lower characteristic bond strengths than those calculated for previous and subsequent ages and for those calculated for 10 % sodium silicate mortar developed using brick clay 2. Characteristic bond strengths after 3 days for the 12 % mortar should be consistently higher or at least similar to those of the 10 % mortar as approximately 97 % of the joints tested after 3 days for both mortars failed through the brick units.

The premature failure of the brick units is related to the test procedure which is too severe for the unfired clay brick units. A joint is tested by clamping the top and bottom brick units separately and then the top unit is loaded (i.e. wrenched) until failure occurs (Figure 4.1). This wrenching action places considerable load on the bottom unit and if failure occurs through the top brick unit the load on the bottom unit would be sufficient to potentially damage the brick and cause premature failure in this brick when loaded to test the next joint. In some cases the consecutive joints cannot be tested as the failure occurs through both the top and bottom units. This is better than having an unsound bottom brick. The damage in the bottom brick is not often noticed unless the failure clearly indicates that the brick was unsound rendering the test of this joint null and void. If this is not the case the average and in particular the characteristic bond strengths calculated will be skewed.

4.8 Conclusion

Sodium silicate mortars, in particular mortars developed from the clays used to manufacture the respective brick units containing sufficient sand to minimise shrinkage on drying, are suitable for the construction of thin walls. At sodium silicate contents of 8 % or higher these mortars, when applied with a trowel to give 3 mm thick joints, gave strengths higher than the 0.2 N/mm^2 required for the 100 mm thick walls to resist the compressive and flexural forces during construction and use. Strengths and bond strengths of these mortars at early ages were good and after 14 days or 28 days the strengths reached a maximum and stabilised with time giving strengths greater than the 0.2 N/mm^2 required at later ages (after 91 days, 1 year and 3 years). Thin sodium silicate unfired clay mortar joints are of a similar cost to standard 10 mm thick cement mortar joints but of substantially lower embodied carbon contents. Thin joints with low embodied carbon are desired to reduce the impact the mortar has on the embodied energy and embodied carbon of the unfired clay masonry.

Although the strengths and bond strengths of 8 % sodium silicate mortars were either similar or stronger to the strengths of the brick units, which are the requirement for masonry construction, the substantially higher strengths and bond strengths of the 10 % and 12 % sodium silicate mortars give walls of higher strength. At these sodium silicate contents the mortars are more flexible and safeguard against problems encountered on-site giving security in construction and eliminating variability.

A high sodium silicate concentration ensures sufficient sodium silicate is available to compensate for thinner joints avoiding problems resulting from irregularities on the surface of the bricks, poor tolerances and irregular sizes of inert particles in the mortar. Variability in water contents, sand contents, shape and size of sand particles (i.e. sand coarseness), clay content and coarseness of the brick clays are also eliminated. At 12 % sodium silicate contents the water contents of the mortars are readily adjusted to give low viscosity mortars suitable for application through dipping of the brick units or application using special tools. The increase in cost and embodied carbon associated with the increase in sodium silicate content from 8 % to 12 % is low and insignificant when compared to the improvement robustness of the sodium silicate unfired clay mortars.

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CHAPTER 5

PROPERTIES OF UNFIRED CLAY MASONRY

5.1 Introduction

An unfired clay block unit (440 mm × 215 mm × 100 mm) and mortar were required to develop a masonry system suitable for construction of thin non-load bearing walls. A block unit and thin mortar joint (3 mm or less) were desired to minimise cost, construction time and mortar usage and compete with low strength concrete block masonry systems used in mainstream construction. A solid unfired clay brick unit (227 mm × 107 mm × 69 mm) extruded from brick clay 2 and sodium silicate clay/sand mortars developed from brick clay 2 gave properties suitable for construction of these standard 100 mm thick walls. The addition of wood-fibre to improve on the properties and reduce weight of the extruded unfired clay masonry units proved beneficial. The inclusion of perforations was also effective in reducing the weight of the unfired clay masonry units.

Prototype block units extruded from brick clay 2 and a robust sodium silicate mortar developed form brick clay 2 were needed to determine the characteristics, properties and format of the blocks, mortar and masonry in order to ascertain the suitability of unfired clay masonry in construction of thin walls. Solid and perforated-block units with and without wood-fibre at 2 % and 4 % by weight were used to determine the influence of perforations and wood-fibre on the properties of the blocks and masonry. These quantities were based on cost and the ability of extrude in a laboratory scale extruded. A mortar containing 12 % instead of 8 % sodium silicate was decided upon to ensure the mortar and mortar bonds were strong enough to overcome inconsistencies during construction, irregularities in the block units and mortar which are both detrimental to thin joints, and give a mortar flexible enough for use in alternative thin joint application methods such as the dipping and special scoop application methods.

The objective of this chapter is to document and discuss the trials to develop the prototype block units, the properties of the prototype block units, mortars and masonry, suitable manufacturing processes to extrude unfired clay blocks containing wood-fibre and finally suggest a block and mortar format for the unfired clay masonry system suitable for construction of thin walls. The aim of the investigation was to:

- organise trials to extrude the prototype blocks
- determine the properties of the prototype blocks
- determine the properties of the masonry
- assess compatibility of commercially available renders and plasters
- determine suitability of standard fixings and fittings into the masonry
- assess influence of wood-fibre and perforations on the properties of the prototype blocks and masonry
- develop a method to manufacture the unfired clay blocks
- formulate a suitable unfired clay block unit, mortar and method of application

The scope of this testing was to determine:

- dimensions of the blocks

- density of the blocks
- compressive strengths of the blocks
- flexural strengths of the blocks
- toughness and water erosion resistance of the blocks
- mortar bond strengths
- compressive strength of the masonry
- flexural strength of the masonry parallel and perpendicular to the bed joints
- initial shear strength of the masonry

5.2 Raw materials

A series of six different prototype unfired clay blocks were required to assess the properties of the block units and masonry and the influence of wood-fibre and perforations on the properties of the blocks and the respective masonry namely:

- solid block without wood-fibre
- solid block with 2 % wood-fibre by weight
- solid block with 4 % wood-fibre by weight
- perforated block without wood-fibre
- perforated block with 2 % wood-fibre by weight
- perforated block with 4 % wood-fibre by weight

Brick clay 2 was used for the manufacture of the prototype unfired clay block units and formulation of the mortar. Brick clay 2 was described as very clayey silt and fine to coarse sand with occasional fine gravel (refer to Chapter 3, Section 3.3 - Table 3.4, Figures 3.4 and 3.5). The clay content is approximately 25 %, which is typical of that used to manufacture fired clay bricks. The mortar was developed by mixing dry 1 part of the finely ground (less than 0.5 mm particle size) brick clay 2 to 3 parts fine builder sand (refer to Chapter 4, Section 4.3.1 - Figures 4.4 and 4.5) and adding 12 % sodium silicate powder by dry weight of the mortar. A softwood fibre (i.e. pine) used in the manufacture of medium density fibre board (MDF) was used in the manufacture of the masonry units. The water content of the wood-fibre ranged from 100 % to 120 % by weight of the wood-fibre.

5.3 Manufacture of prototype unfired clay blocks

A die of 260 mm in width and 125 mm in height (refer to Chapter 2, Section 2.9.3 – Figure 2.3) was used to extrude block units (250 mm × 250 mm × 120 mm), half-block units (125 mm × 250 mm × 120 mm) and brick units (250 mm × 70 mm × 120 mm). Dimensions of the units given were those expected after oven-drying. Half block units were extruded to simplify the construction of the wall panels to determine compressive and flexural strengths of the masonry, and the brick units to determine density and compressive strength of the masonry units, and mortar bond strengths using the bond wrench test method. A staggered rectangular perforation pattern, which assists drying, was chosen for the perforated masonry units (Figure 5.1 and refer to Chapter 2, Section 2.9.3 - Figure 2.3).

The trial to manufacture the prototype blocks was only partially successful. Solid and perforated units without wood-fibres were successfully manufactured (each batch containing 50 brick units, 250 block units and 120 half-block units) whereas only perforated units containing wood-fibre at an uncertain percentage were manufactured (60 brick units, 280 block units and 150 half-block units) due to difficulties experienced with the addition of the wood-fibre to the clay. The wood-fibre caused blockages in various parts of the brick manufacturing process.

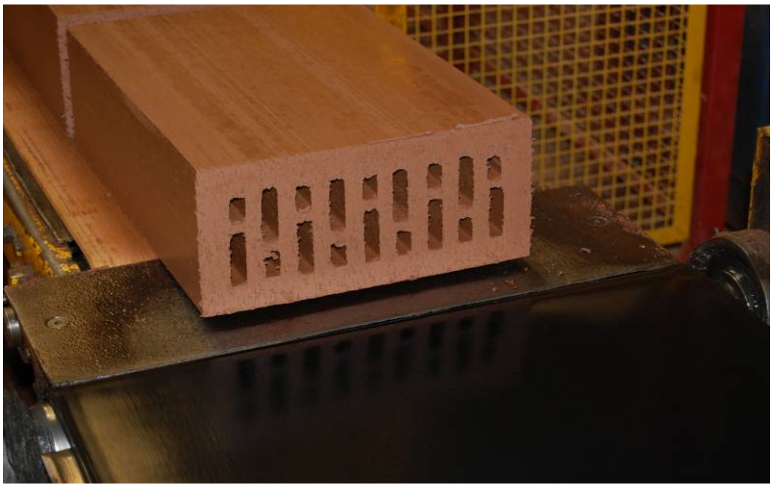

Figure 5.1 Extrusion of perforated block units showing wire cut face at right angles to the direction of extrusion

At first wood-fibre at 2 % by weight was premixed into the raw brick clay, obtained directly from the quarry, in the storage bay area at the start of the process using a front-end loader. The mixture was then fed into the roller pan grinders at the main plant in an attempt to attain a homogeneous clay/wood-fibre mixture. On grinding, the clay and wood-fibre blocked the sieve at the bottom of the pan due to the high moisture content of the wood-fibre causing the clay to ball on mixing. A build-up of the clay and wood-fibre occurred at the bottom of the pan, which required digging out. The run was aborted and the 2 % clay/wood-fibre mixture was not reused.

On the second attempt, the amount of clay flowing into storage silos with time was calculated, and the wood-fibre to give a 2 % content by weight was added by hand into the silo with the ground clay. The clay and wood-fibre appeared to mix adequately (Figure 5.2a) and perforated brick units, block units and half-block units containing wood-fibre were extruded. After the change over of the die to produce the solid wood-fibre units the extruder failed to operate correctly. The extruded clay was too soft and snaked all over the place (Figure 5.2b). At this point the process was shut down and it was found that there were blockages in the silos and in the extruder.

Clay and wood-fibre were not effectively mixed in the silo. Clay displaced the low weight wood-fibre in the silo and flowed at a faster rate from the silos causing a substantial increase in the wood-fibre concentration within the silo from the bottom to the top. Owing to the bulkiness of the wood-fibre the outlets of the silos and disperser responsible for breaking up the clay mixture prior to extrusion clogged up over time. As a result the brick units which were made first, were of a lower wood-fibre content (i.e. less than 2 %) and the half block units which were made last, were of a higher wood-fibre content (i.e. greater than 2 %). The snaking of the half-block solid wood-fibre units, which were run directly after the perforated half-block units, was due to the high wood-fibre content of the mixture giving insufficient vacuum during extrusion.

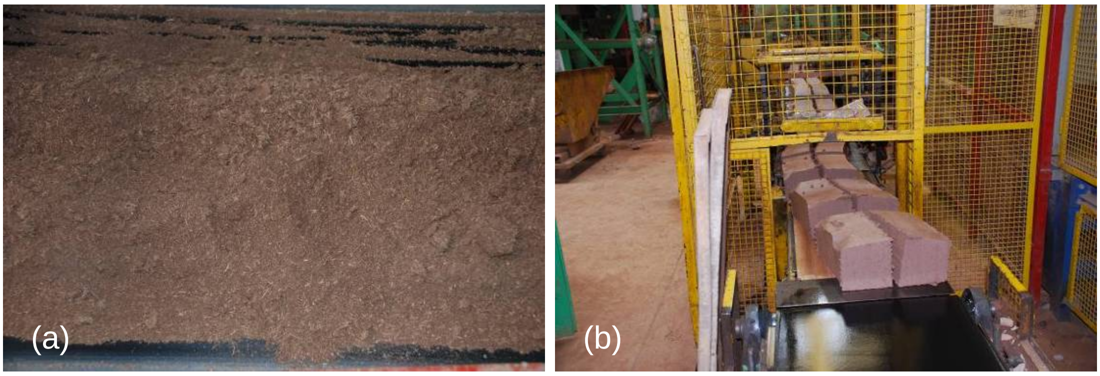

Figure 5.2 (a) Appearance of clay and wood-fibre mixture on conveyor feeding the mixers (b) snaking of solid wood-fibre blocks

Because of the substantial cost involved in running the trial, it was decided not to repeat it. Meaningful and decision making results were obtained from the unfired clay masonry units produced. The influence of wood-fibre on the properties of the unfired clay masonry was comprehensively assessed by comparing the properties of the masonry units and masonry constructed from the respective units. The influence of perforations on the unfired clay masonry was determined by comparing properties of the solid masonry without wood-fibre to those of the perforated masonry without wood-fibre. The influence of wood-fibre on the unfired clay masonry was determined by measuring the amount of wood-fibre in the perforated units and then comparing the properties of the masonry to those of the solid and perforated masonry without wood-fibre.

5.4 Properties of the prototype unfired clay blocks

An investigation was done to identify the characteristics of the masonry units produced namely those of the perforated wood-fibre masonry units produced and then to determine and asses the properties of the masonry units that were necessary for this stage of the investigation such as:

- appearance and handling
- wood-fibre contents
- dimensions and density
- compressive strengths
- flexural strengths
- toughness and water erosion resistance

5.4.1 Appearance and handling of the unfired clay masonry units

Tolerances on the block and half-block units were poor. The bottom face with respect to the extruded clay column on the conveyor belt of the block units was significantly longer than the top face (i.e. up to 4 mm longer for the solid block units without wood-fibre). This indicates that the green blocks sagged under their weight after extrusion and wire cutting, which generally occurs when the water content is too high. Tolerances of the heavier solid blocks were therefore noticeably worse than those of the lighter perforated blocks. The tolerances of the perforated blocks containing wood-fibre were the best due to the increased stability imparted by the wood-fibre on the wet clay.

Shrinkage cracks were evident in a number of the solid block and half-block units but not in the solid brick units. This was due to the oven-drying of the larger volumes of clay at 100 °C. Similar cracks were also evident on some of the perforated blocks without wood-fibre but these were probably due to handling (stacking and transport) rather than drying shrinkage as a number of the brick and half block units broke on handling. No cracks or breakages were detected in the perforated units containing the wood-fibre.

Wire cutting the extruded clay and wood-fibre mixture presented no problems. Cut faces of the perforated wood-fibre masonry units were smoother than that of the masonry units without wood-fibre. Scratch marks from the gravel in the mixture were far less noticeable on the cut surfaces of the wood-fibre units giving them a far better appearance than the units without wood-fibre and the wood-fibre units felt sound in comparison.

5.4.2 Determination of wood-fibre contents

A rudimentary investigation was done to estimate the wood-fibre content of the perforated masonry units extruded. A representative portion (1000 kg) of the units was dissolved in water. The mixture was agitated to suspend the wood-fibre in the solution, which was then passed through a 2 mm sieve to collect the wood-fibre. The wood-fibre was dried to a constant mass at 105 °C and the percentage by weight in the masonry units was calculated. The wood-fibre content of the brick units (average of 0.45 %) was substantially lower than that of the block (1.69 %) and half-block (2.80 %) units. This was directly related to the clay displacing the wood-fibre as it flowed into the silo giving rise at first to the low wood-fibre mixture from which the brick units were made and then the higher wood-fibre mixtures from which the block and half-block units were made.

5.4.3 Dimensions and density

The dimensions of the brick sized units were measured (BS EN 772-16:2000) and the density was determined using the gross density method (BS EN 772-13:2000). Dimensions of the different brick units were similar (255 mm × 120 mm × 68 mm). The net density of the solid brick units (2119 kg/m^3) was higher than that of the perforated units without wood-fibre (2064 kg/m^3). The density of the perforated wood-fibre units was the lowest (2042 kg/m^3) which was expected as the wood-fibre has lower density than the clay.

5.4.4 Compressive strength

Compressive strengths of the solid, perforated and perforated wood-fibre masonry units (i.e. the brick, half-block and block sized units) were determined (BS EN 772-1:2000). Specimens were capped and conditioned at 20 °C and 60 % - 65 % RH for 28 days. Compressive strengths of capped solid, perforated and perforated wood-fibre brick units conditioned for 7 days and 14 days were determined to confirm time required for the stabilisation of unfired clay masonry units with respect to moisture content and compressive strength. The influence of moisture on compressive strength was determined on the solid, perforated and perforated wood-fibre brick units. Compressive strengths were determined on capped units directly after oven-drying at 105 °C for 24 hours and on capped units at various moisture contents (i.e. brick units sprayed with water to attain different moisture contents up to 10 % then capped and allowed to normalise for 7 days in a sealed plastic bag at 20 °C and 60 % - 65 % RH). Compressive strengths were determined using a conventional compression testing machine at a loading rate of 45 N/s. Moisture contents of the brick units were determined after failure (i.e. measuring change in mass on drying a sample at 105 °C for 24 hours).

After 28 days the moisture contents of the solid, perforated and perforated wood-fibre masonry units (1.81 % to 2.06 %) were similar (Table 5.1). Compressive strength (average of six determinations) of the solid brick units (4.42 N/mm^2) was significantly higher than those of the other masonry units tested, which ranged from 3.12 N/mm^2 to 4.02 N/mm^2 (Table 5.1). Compressive strengths of the brick units were higher than those of the respective half-block and block units due to the tall slender shape of the block sized specimens. Applying the shape factors quoted in the British Standard (BS EN 772-1:2000) gave incoherent results, for example, the strength of the solid brick unit (shape factor of 0.8) equates to 3.54 N/mm^2 and 4.63 N/mm^2 and 4.20 N/mm^2 respectively for the solid half-block and solid block units (shape factor of 1.30).

Table 5.1 Compressive strength (N/mm^2) and moisture content (%) of masonry units capped and normalised at 20 °C and 60 % - 65 % RH for 28 days (variation in compressive strength from the mean were less than 5 %)

Masonry unit	Moisture Content (%)	Gross Strength (N/mm^2)	Net Strength (N/mm^2)
Solid brick	2.06	4.42	4.42
Perforated brick	2.04	2.88	3.86
Wood-fibre brick (0.45 %)	2.06	2.97	4.02
Solid half block	1.84	3.56	3.56
Perforated half block	1.81	2.58	3.46
Wood-fibre half-block (2.80 %)	2.08	2.30	3.12
Solid block	1.96	3.23	3.23
Perforated block	1.90	2.35	3.16
Wood-fibre block (1.69 %)	2.01	2.40	3.26

Compressive strengths of the perforated brick units containing 0.45 % wood-fibre (4.02 N/mm^2) were higher than those of the perforated brick units without wood-fibre (3.86 N/mm^2). Compressive strengths of the perforated block units containing 1.69 % wood-fibre content were similar to those of the perforated block units without wood-fibre (3.26 N/mm^2 and 3.16 N/mm^2 respectively). Compressive strengths of the perforated half-block units containing 2.80 % wood-fibre (3.12 N/mm^2) were lower than those of the perforated half-block units without wood-fibre (3.46 N/mm^2).

A minimum of 28 days was required for the unfired clay materials to normalise at 20 °C and 60 % - 65 % RH. After 28 days the compressive strengths and moisture contents of the brick units were expected to remain stable as moisture contents for the respective brick units were similar, i.e. approximately 2 %, which is a moisture content typical of unfired clay materials at ambient conditions (Table 5.2).

Table 5.2 Net compressive strengths (N/mm^2) and moisture contents (%) of brick units capped and normalised at 20 °C and 60 % - 65 % RH (variation in the compressive strengths from the mean were less than 5 %)

Age	**Solid**		**Perforated**		**Wood-fibre**	
(days)	Moisture	Strength	Moisture	Strength	Moisture	Strength
7	2.54	3.82	2.24	3.72	2.48	3.74
14	2.13	3.99	2.15	3.77	2.36	3.81
28	2.06	4.42	2.04	3.86	2.06	4.02

Net compressive strengths of the solid, perforated and wood-fibre brick units sharply decreased at similar rates with an increase in moisture content from 0.50 % to 2.00 % (Figure 5.3). After 2.00 % moisture content the compressive strengths decreased at similar but slower rates with an increase in moisture content. Compressive strengths of the solid brick units were higher than the net compressive strengths of the perforated brick units and perforated wood-fibre brick units. At moisture contents of less than 2 % the strengths of the perforated and perforated wood-fibre brick units were similar. Strengths of the perforated wood-fibre brick units were higher than those of the perforated units at moisture contents greater than 2 %.

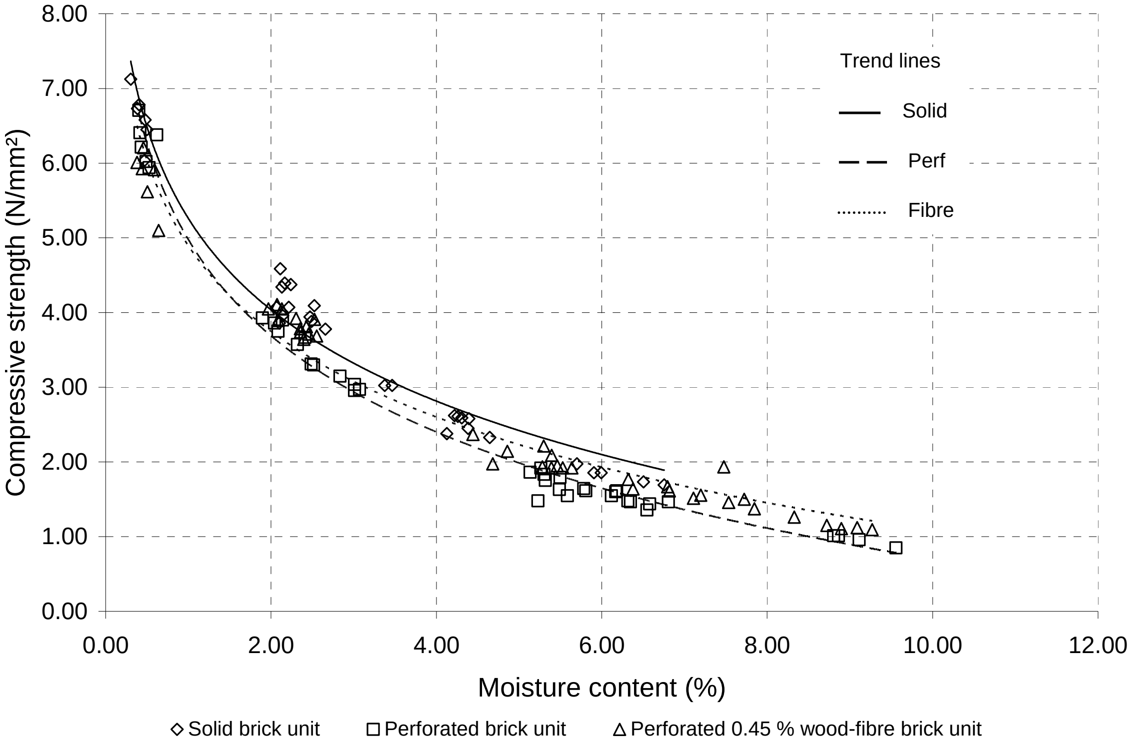

Figure 5.3 Net compressive strengths versus moisture contents for solid, perforated and perforated wood-fibre brick units

Net compressive strengths of the solid, perforated and perforated wood-fibre specimens (i.e. brick, half-block and block sized masonry units) were all acceptable for the construction of 100 mm thick walls (i.e. higher than the 2.50 N/mm^2 required for thin wall construction). Compressive strengths of the specimens were however markedly influence by the perforations. Gross compressive strengths of the perforated specimens with and without wood-fibre were significantly lower than those of the solid specimens. Gross strengths of the perforated wood-fibre half block specimens and the perforated block specimens with and without wood-fibre were lower than the 2.5 N/mm^2 required for thin-wall construction. Gross compressive strengths higher than 3.00 N/mm^2 are ideal to ensure the unfired clay masonry units are robust enough for use on-site in the construction of non-load bearing walls.

Compressive strengths of the masonry units were not significantly influenced by the wood-fibre. Wood-fibre gave an improvement in compressive strength for the perforated brick units and perforated block units but gave a decrease in compressive strength for the perforated half-block units. The lower compressive strength was due to the higher moisture contents of the perforated wood-fibre half-block units (2.08 %) compared to those of the perforated half-block units without wood-fibre (1.81 %) rather than the high wood-fibre content of the half-block units (2.80 %). The higher moisture content was related to the high wood-fibre content. The wood-fibre has a higher equilibrium moisture content at ambient conditions than the unfired clay (i.e. 16 % as opposed to 2 % at 20 °C and 60 % RH) making the impact at high wood-fibre contents on the overall moisture content more significant.

The compressive strengths obtained for the unfired clay materials above correlates with previous test results where no substantial variations in compressive strengths were observed for hand-extruded specimens at 1 %, 2 % or 3 % wood-fibre contents (Chapter 3, section 3.5.3 – Table 3.6).

5.4.5 Flexural strengths

The flexural strengths of the brick units and half-block units were measured using the three-point bending test method (Chapter 3, Section 3.4.3). The flexural strengths were measured over the width of the brick units (i.e. 0° or in direction of extrusion, refer to Figure 5.4) and over the face of the half-block units (i.e. 90° to the direction of extrusion, refer to Figure 5.4). A load rate of 0.5 mm/min was applied until failure. The flexural strengths of the block units were not measured using the three-point bending test due to size constraints of the test rig. The flexural strengths of the block sized units were assessed using the wrenching apparatus used in the method to determine mortar bond strengths (refer to BS EN 1052-5:2005). Flexural strengths were determined over the face of the block units (i.e. at 0° and 90 ° to direction of extrusion, refer to Figure 5.4).

Gross flexural strengths of the solid brick units (1.56 N/mm^2) were significantly higher than those of the perforated (0.51 N/mm^2) and perforated wood-fibre (0.49 N/mm^2) brick units (Table 5.3). Gross flexural strengths of the perforated half-block units (0.72 N/mm^2) were significantly lower than those of the perforated wood-fibre (1.11) N/mm^2) and solid (1.09 N/mm^2) half-block units.

Gross flexural strengths measured in the direction of extrusion of the solid block units (0.51 N/mm^2) were significantly higher than those of the perforated wood-fibre block units (0.31 N/mm^2) and those of the perforated block units without wood-fibre (0.18 N/mm^2), which were substantially lower (Table 5.4). Gross flexural strengths measured at right angles to the direction of extrusion of the perforated wood-fibre block units (0.84 N/mm^2) were significantly higher than those of the solid block units (0.54 N/mm^2) and substantially higher than those of the perforated block units without wood-fibre (0.39 N/mm^2), i.e. gross flexural strengths at right angles to the extrusion direction of the perforated wood-fibre block units were more than double those of perforated block units without wood-fibre (Table 5.4).

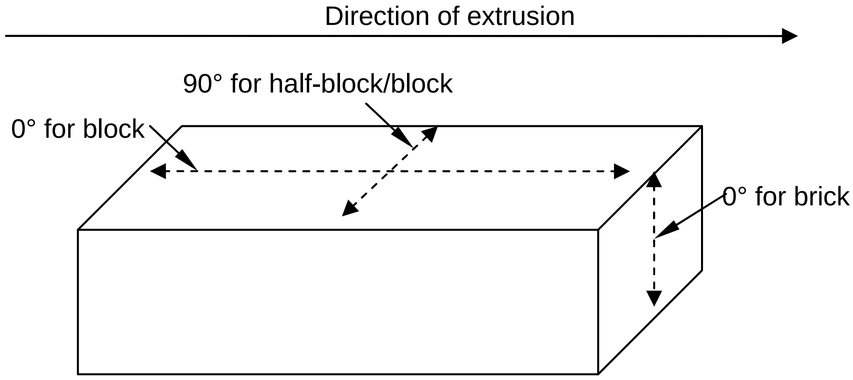

Figure 5.4 Schematic showing loading of brick, half-block and block units to determine the flexural strengths of the masonry units

Table 5.3 Flexural strengths (measured using the three-point bending test method) and moisture contents of brick and half-block units

Masonry unit	Moisture Content (%)	Gross Strength (N/mm^2)
Solid brick	1.33	1.56
Perforated brick	1.59	0.51
Wood-fibre brick (0.45 %)	1.67	0.49
Solid half block	1.62	1.09
Perforated half block	1.53	0.72
Wood-fibre half-block (2.80 %)	1.68	1.11

Table 5.4 Flexural strengths (assessed using the bond wrench test method) and moisture contents of block units

Bending direction	Moisture Content (%)	Gross Strength (N/mm^2)
Solid block (0°)	2.04	0.51
Perforated block (0°)	1.62	0.18
Wood-fibre block (1.69 %) (0°)	1.90	0.31
Solid block (90°)	2.04	0.54
Perforated block (90°)	1.62	0.39
Wood-fibre block (1.69 %) (90°)	1.90	0.84

Gross flexural strengths measured at right angles to the direction of extrusion of the solid block units were similar to those measured in the direction of extrusion.

Gross flexural strengths measured at right angles to the direction of extrusion of the perforated wood-fibre block units were almost treble and those of the perforated block units without wood-fibre more than double those measured in the direction of extrusion (Table 5.4).

The higher flexural strengths of the solid brick units compared to those of the perforated brick units with and without wood-fibre were due to the lower moisture contents (Table 5.3) of the solid brick units (1.33 %, 1.67 % and 1.59 % respectively). Although flexural strengths of the perforated brick units with and without wood-fibre were similar the higher moisture content of the wood-fibre units indicates that the 0.45 % wood-fibre content improves the flexural strength and toughness of the unfired clay material.

The higher flexural strength of the perforated half-block units without fibre compared to those of the solid half-block units without wood-fibre was due to the lower moisture content of the perforated half-block units (1.62 % and 1.53 % respectively). The higher gross flexural strengths and significantly higher net flexural strengths of the perforated wood-fibre half-block units compared to those of the solid and perforated half-block units without wood-fibre was directly related to the high wood-fibre content in the perforated half-block units (2.80 %) and the orientation of the wood-fibres in the direction of extrusion.

The gross flexural strengths of the perforated block units with and without wood-fibre were substantially lower in the direction of extrusion than those at right angles to the direction of extrusion due to the longitudinal orientation of the perforations to the wrenching direction in the direction of extrusion. The perforations were at right angles to the direction of wrenching when tested at right angles to the direction of extrusion giving the blocks better resistance to bending. The gross flexural strength of the perforated block units without wood-fibre in the direction of extrusion was lower than the 0.2 N/mm^2 required for thin-wall construction. This was due to lower than average measurements, for example, 0.05 N/mm^2 and 0.08 N/mm^2, related to the variability associated with the longitudinal orientation of the perforations when tested in the direction of extrusion.

The bond wrench tests show that wood-fibre at a content of 1.69 % substantially improves the flexural strengths of the perforated block units both in the direction of extrusion and at right angles to the direction of extrusion. The substantially higher improvement at right angles to the direction of extrusion was due to the alignment of the wood-fibres in the direction of extrusion giving the block better resistance to bending when tested in this manner. Net flexural strengths estimated clearly show the substantial improvement the wood-fibre has on the flexural strength and toughness of the unfired clay material. Net flexural strengths (Table 5.4) of the perforated wood-fibre block units (0.70 N/mm^2) were substantially higher than those of the solid block units in the direction of extrusion (0.51 N/mm^2) and almost three times higher (1.46 N/mm^2) than those of the solid block units at right angles to the direction (0.54 N/mm^2).

5.4.6 Impact resistance and water erosion resistance

A rudimentary investigation was done to assess the impact resistance and water-erosion resistance of the unfired clay masonry (i.e. solid block units without wood-fibre, perforated block units without wood-fibre and perforated wood-fibre block units). The blocks were dropped from a height of 100 cm directly onto one of the corners (i.e. a similar procedure to that described by Walker, 2005). The percentage mass losses with the number of drops were recorded. Impact resistance was measured as the number of drops required to fracture the block units. The water-erosion resistance was measured by spraying a jet of water from a standard garden hose onto a face of the block unit from a distance of 20 cm (i.e. a similar procedure to that described by Minke, 2000). The depth and diameter of the hole was measured with time. The erosion resistance was equated to the size of the hole with time.

After one drop the mass losses of the perforated block units without wood-fibre were substantially higher than those of the solid block units without wood-fibre and those of the perforated wood-fibre block units (Figure 5.5). The solid block units lost less mass than the perforated wood-fibre block units up until six drops. After six drops the solid block units lost significantly more mass than the perforated wood-fibre block units (Figure 5.5). The corner of the perforated block units completely broke off after one drop (Figure 5.6). At six drops the corners of the solid block units without wood-fibre and those of the perforated wood-fibre block units showed signs of crushing. The solid block units fractured in two after six drops whereas the perforated wood-fibre block units only fractured at the corner and continued to resist further impacts fracturing again after nine and eleven drops (Figure 5.5).

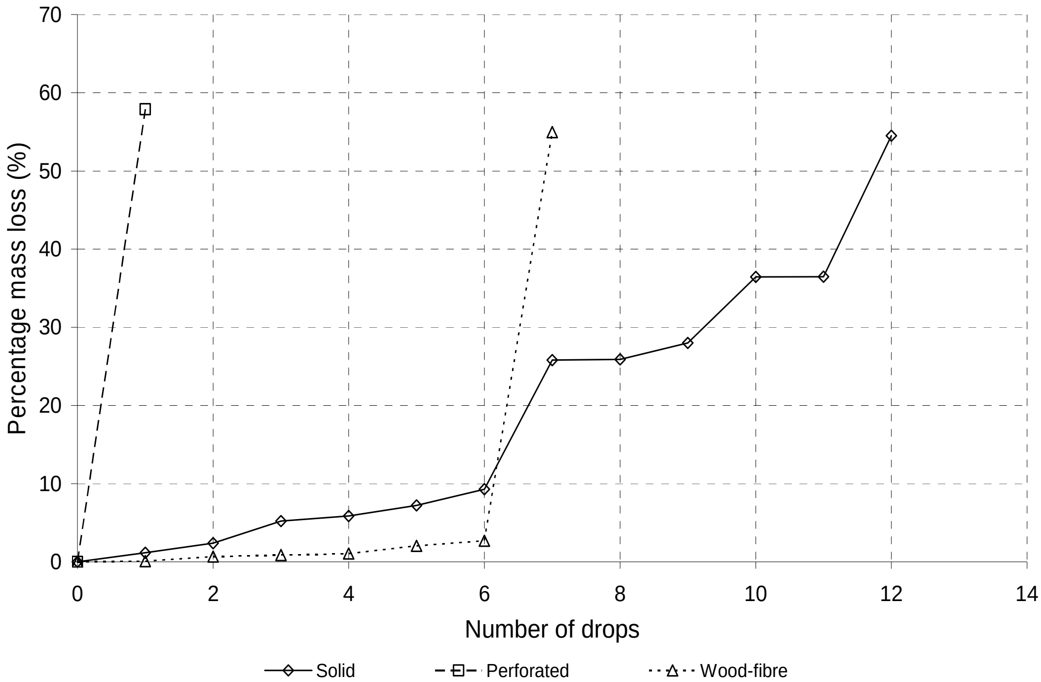

Figure 5.5 Percentage mass losses with number of drops of solid and perforated block units without wood-fibre, and perforated wood-fibre block units

The results show wood-fibre significantly improves the toughness and durability of the unfired clay material. Including perforations has the opposite effect on the blocks. The impact resistance of the perforated block format was improved substantially and even after 10 drops the perforated wood-fibre blocks were usable in that a half block unit could be cut from the fractured block unit whereas the solid block fractured into two after six drops. Water-erosion showed that the wood-fibre significantly reduced the amount of material lost with time. After spraying the unfired clay blocks for two minutes the material lost from the perforated wood-fibre block units was half that lost from the perforated and solid block units without wood-fibre (Figure 5.7).

Figure 5.6 Drop tests showing failures from left to right of a perforated wood-fibre block after six drops, a solid block unit without wood-fibre after six drops and a perforated block unit without wood-fibre after one drop

Figure 5.7 Water-erosion tests showing from left to right a perforated wood-fibre block unit with smaller shallower hole than a perforated block unit without wood-fibre and a solid block unit without wood-fibre

5.5 Masonry tests

Masonry tests were done on stacks and wall panels constructed from the solid and perforated masonry units extruded in the trial. The 12 % sodium silicate mortar developed from the finely ground brick clay 2 in a ratio of 1 part clay to 3 parts sand was used. The format of the stacks and wall panels depended on the size of the masonry units and the standard test method used. Standard masonry test methods used were the method to determine mortar bond strengths of horizontal bed joints in masonry (BS EN 1052-5:2005), the method to determine compressive strength of the masonry (BS EN 1052-1:1999), the method to determine flexural strength of the masonry (BS EN 1052-2:1999) and the method to determine initial shear strength of the horizontal bed joints in masonry (BS EN 1052-3:2002).

Stacks to determine mortar bond strengths and initial shear strengths of the horizontal bed joints in the masonry were prepared using the extruded brick units or brick sized units cut from the extruded block units. Wall panels to determine compressive and flexural strengths of the masonry were constructed from the block and half-block sized units prepared. Mortar was not applied to the perpendicular joints of the wall panels. A block ultimately desired for construction was one with profiled perpendiculars which would not require mortar thereby speeding construction and reducing mortar usage.

Wall panels were constructed by a professional brick-layer to assess the feasibility of using the unfired clay blocks and mortars for the construction of walls on-site. Scoop and dipping application methods were used to apply the mortar and mortar beds were not adjusted to compensate for the poor tolerances of the masonry units (i.e. the emphasis was to achieve a thin mortar joint with consistency similar to that used on-site for the scoop and dipping methods). The dipping method was predominantly used to lay the perforated masonry units. The scoop method failed to deliver sufficient mortar over the perforations to give a consistent 2 mm thick joint and resulted in considerable wastage of the mortar down the perforations. The scoop application method (refer to Chapter 4, Section 4.3.5 - Figure 4.10) was predominantly used to lay the solid masonry units. Dipping failed to entirely coat the surface of the solid masonry units and was difficult due to the weight of the solid block units in particular.

Stacks were constructed without experiencing any problems. Construction of the wall panels was problematic. The poor tolerances of the block and half-block units made it difficult to construct well-ordered sound wall panels using thin mortar joints (3 mm or less) in particular joints applied using the scoop and dipping methods. Wall panels were skewed and gaps of up to 10 mm wide were evident in the vertical joints due to the poor tolerances of the block sized units (Figure 5.8). The heavy weight of the units made it difficult to lay the bed joint at varying thickness.

Figure 5.8 Wall panels constructed for the determination of compressive strength of the masonry showing disordered unsound construction due to the poor tolerances of the half-block and block sized units extruded

5.5.1 Mortar bond strengths of horizontal bed joints in masonry

Mortar bond strengths were measured on stacks prepared from the solid, perforated and wood-fibre brick units using the bond wrench method (BS EN 1052-5:2005). Stacks of the solid brick units without wood-fibre were made by applying the 12 % sodium silicate clay mortar at a water content of 26 % with the special scoop. Stacks of the perforated brick units with and without wood-fibre were made by dipping the brick units into the 12 % sodium silicate clay mortar at a water content of 26 %. Mortar joints of 1 mm to 3 mm thick were obtained in all of the stacks prepared. Stacks were conditioned at 20 °C and 60 % - 65 % RH for 28 days prior to testing using the bond wrench apparatus

Average bond strengths (average of twelve determinations) of the solid and perforated brick units without wood-fibre were similar (0.39 N/mm^2) and higher than that of the perforated wood-fibre brick units (0.31 N/mm^2). The characteristic bond strength of the solid brick units (0.28 N/mm^2) was higher than that of the perforated brick units without fibre (0.23 N/mm^2). The characteristic bond strength of the perforated wood-fibre units (0.11 N/mm^2) was significantly lower than those of the solid and perforated brick units without wood-fibre (Table 5.5).

Table 5.5 Bond strengths of scoop applied and dipped 12 % sodium silicate brick clay 2 mortars conditioned at 20 °C and 60 % - 65 % RH for 28 days (Stdev – standard deviation)

Brick units	**Bond Strength** (N/mm^2)			
	Average	Characteristic	Stdev	Range
Solid	0.39	0.28	0.07	0.20
Perforated	0.39	0.23	0.09	0.31
Wood-fibre (0.45 %)	0.31	0.11	0.16	0.41

Modes of failure for the joints in the solid brick unit stacks and the perforated brick unit stacks with and without wood-fibre were all due to failure within the brick units, that is either from the brick unit delaminating onto the mortar (Figure 5.9a, 5.9b and 5.9c) or directly through the brick unit (Figure 5.9d). Seven out of twelve joints for the solid brick units, nine out of twelve joints for the perforated brick units without wood-fibre and ten out of twelve joints for the perforated wood-fibre brick units failed through the brick delaminating onto of the mortar.

Characteristic bond strengths for the solid and perforated brick unit stacks without wood-fibre indicate that the 12 % sodium silicate mortar developed form brick 2 were suitable for the construction of 100 mm thick walls using the scoop and dipping application methods (i.e. bond strengths of all the joints tested were higher than the 0.2 N/mm^2 required). The exception was with the perforated brick units where the characteristic bond strength was significantly lower than the 0.2 N/mm^2 required. This was due to poor bond strengths measured in all the joints of one of the four stacks tested (i.e. 0.16 N/mm^2, 0.18 N/mm^2 and 0.18 N/mm^2) and a poor joint in each of the other two stacks (i.e. 0.16 N/mm^2 and 0.19 N/mm^2 – Figure 5.10a, 5.10b and 5.10c). The bond strengths of the joints in the other remaining stack (0.57 N/mm^2 – Figure 5.10d) were higher than those measured for the joints in the solid and perforated brick unit stacks without wood-fibre.

The higher than average bond strength measurements and the modes of failure suggest that the poor bond strengths in the perforated wood-fibre brick unit stacks were not due to mortar but related to the brick units or mortar application methods. None of the failures in the solid, perforated and perforated wood-fibre stacks were through the mortar or from the mortar de-bonding at the interface and on average the bond strengths of the joints were significantly higher than 0.2 N/mm^2. This indicates that that the strength and bond strength of the mortar was similar or higher to that of the brick units and that the scoop and dipping application methods giving a 1 mm to 3 mm joint with the 12 % sodium silicate mortar developed from brick clay 2 were suitable but not ideal.

Figure 5.9 Modes of failure after 28 days of 1mm to 3 mm thick scoop applied and dipped 12 % sodium silicate brick clay 2 mortar joints a) perforated brick units without wood-fibre, b) perforated brick units with 0.45 % wood-fibre and c) solid brick units without wood-fibre showing brick delaminating onto mortar at interface, and d) failure directly through solid brick units without wood-fibre

Scoop and mortar application methods were more variable than the trowel application method. Scoop and dipping methods failed to completely coat the surfaces of the brick units and also gave thinner joints which were susceptible to poor tolerances and irregularities on the surfaces of the brick units. The poor areas of bonding within the joint act as stress raisers during the wrenching of the stacks and result in the propagation of cracks through the masonry units directly above the bond interface. As a result, failures of the brick onto the mortar bond were more common than failures directly through the brick units.

An additional four stacks were made from the perforated brick units containing the wood-fibre using the 12 % sodium silicate mortar to check the bond strengths of the joints. Stacks were carefully dipped into the mortar at 26 % water content to ensure a joint of at least 3 mm thick was obtained. Stacks were conditioned at 20 °C and 60 % - 65 % RH for 28 days prior to measuring mortar bond strengths.

Average and characteristic bond strengths (average of twelve determinations) were substantially higher than those from the previous perforated wood-fibre brick units and those from the solid and perforated brick units without wood-fibre (i.e. 0.58 N/mm^2 and 0.40 N/mm^2 respectively). Modes of failure were mainly directly through the brick units (ie. ten out of the twelve joints failed directly through the brick units and only two failed from the brick unit delaminating onto the mortar).

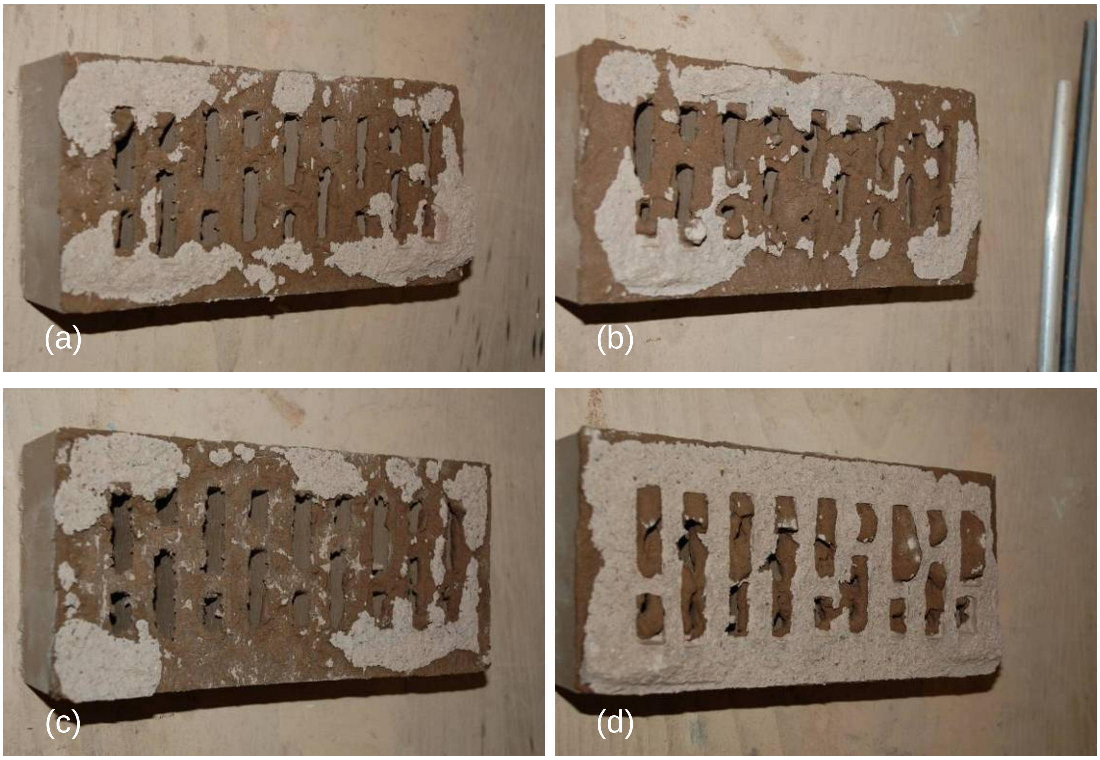

Figure 5.10 Modes of failure after 28 days of 3 mm dipped 12 % sodium silicate brick clay 2 mortar joints in perforated 0.45 % wood-fibre brick unit stacks a), b) and c) failures related to poor mortar bond strengths d) failure related to good mortar bond strengths

Variability in the bond strength measurements using the 3 mm thick joints were reduced and bond strengths of all the joints were substantially higher than that required for thin wall construction (i.e. bond strengths of the twelve joints tested ranged from 0.41 N/mm^2 to 0.74 N/mm^2). Modes of failure indicate that the 3 mm thick joints gave strengths and bond strengths higher than that of the perforated brick units with a wood-fibre content of 0.45 %. The bond strengths were lower to the gross bending strengths of the perforated block units with a wood-fibre content of 1.69 % (0.84 N/mm^2 – Table 5.4). A 3 mm joint would therefore give similar mortar strengths and bond strengths to masonry units containing higher wood-fibre contents making the mortar more suitable for the construction of thin-walls using masonry units containing wood-fibre.

The results confirm that the 12 % sodium silicate mortar developed from brick clay 2 gives strengths and bond strengths suitable for the construction of thin walls. A 3 mm thick joint is necessary to eradicate the problems associate with thinner joints (i.e. 1 mm to 2 mm thick joints common with low viscosity mortars used for scoop and dipping application methods). The 3 mm thick joints ensure that surface irregularities and poor tolerances of the masonry units have a minimal impact on bond strengths and that sufficient sodium silicate solution is available to give the unfired clay mortar strengths and bond strengths similar to the higher flexural strengths of unfired clay masonry containing wood-fibre thus optimising the strength of the unfired clay wall.

A rudimentary investigation was done to determine the influence of using the coarser clays used for the manufacture of bricks to develop the 12 % sodium silicate mortars (i.e. not finely grinding the brick clays sourced to give good retention of the sodium silicate solution in the mortars) and to incorporate plant-fibre into the 12 % sodium silicate coarse clay mortars developed to minimise wastage of the mortar into the perforations.

The wastage of mortar down the perforations was determined using a 12 % sodium silicate unfired clay mortar developed using 1 part of the coarser brick clay 2 sourced directly from the factory to 3 parts fine builder sand. The influence of plant-fibres on mortar wastage was determined by developing an additional four mortars from the coarse clay mortar containing plant-fibres namely chopped straw (5mm to 20 mm lengths), the MDF wood-fibre, the GMF wood-fibre and chopped flax (5 mm to 20 mm lengths) at a 1 % concentration by weight. A known amount of mortar (i.e. approximately that required to give a 5 mm joint) at a water content of 26 % was applied using a trowel onto the surface of a perforated brick unit. The mortar was scrapped off the surface and weighed to determine the percentage of the mortar lost down the perforations.

Approximately 27 % of the coarse clay mortar without the plant-fibre was lost down the perforations on application. Substantially less mortar was lost down the perforations with the GMF (11 %), chopped straw (5 %) and chopped flax (4 %) fibres whereas the MDF (24 %) failed to significantly reduce the loss of the mortar down the perforations.

The influence of the coarser clay and plant-fibres on mortar bond strengths were determined on stacks prepared from brick sized specimens cut from the perforated unfired clay blocks containing 1.89 % wood-fibre using the 12 % sodium silicate coarse clay mortar and those containing 1 % chopped straw and 1 % chopped flax. Mortars at a water content of 26 % (i.e. similar to that used in the scoop and dipping application methods) were applied using a trowel to give joints of 5 mm thick. The thicker joints were used to ensure the inert particles in the coarser clay and the plant-fibres have a minimal impact on the mortar bond strengths and to provide sufficient sodium silicate solution to overcome the impact of the coarse particles and plant-fibres have on the bond strengths. Stacks were conditioned at 20 °C and 60 % - 65 % RH for 14 days prior to testing.

The average bond strength of the four 5 mm thick joints tested for the coarse clay mortar without plant-fibre (0.37 N/mm^2) was substantially lower than that of the fine clay mortar applied using the dipping method above and trowel method (refer to Chapter 4, Section 4.3.3 – Table 4.3) to give a 3 mm thick joint (0.58 N/mm^2 and 0.55 N/mm^2 respectively) but comparable to the 1 mm to 3 mm thick joints prepared using the scoop and dipping application methods (0.39 N/mm^2, and 0.39 N/mm^2 and 0.31 N/mm^2 respectively). The two coarse-clay straw 5 mm mortar joints tested (0.31 N/mm^2 and 0.41 N/mm^2) gave bond strengths similar to the four 5 mm coarse clay joints without wood-fibre (i.e. 0.30 N/mm^2, 0.38 N/mm^2, 0.38 N/mm^2 and 0.41 N/mm^2) whereas those of the flax mortar gave a joint of a significantly lower strength (0.18 N/mm^2) and a significantly higher strength (0.55 N/mm^2).

The significant difference between the 12 % sodium silicate clay mortar joints was that the modes of failure of the coarse clay joints with and without plant-fibre were all through the mortar with the exception of one joint without the plant fibre which failed through the brick unit (Figure 5.11) whereas those for the fine clay mortar joints were through the brick units or from the brick units delaminating onto the mortar.

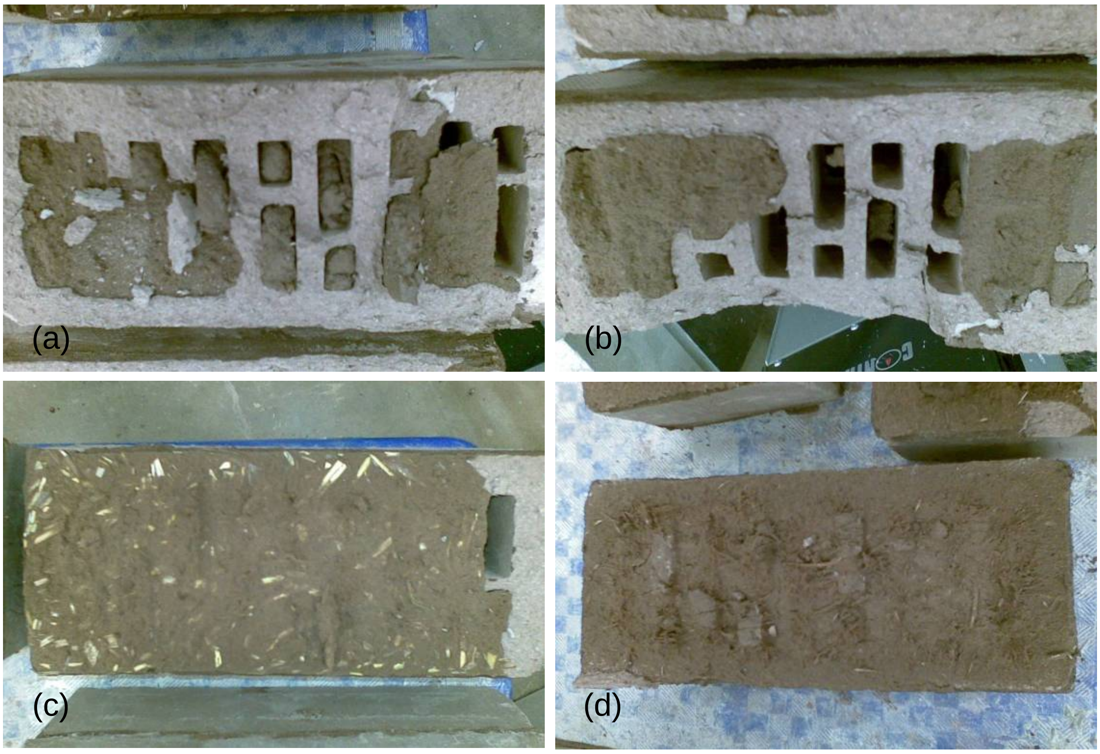

Figure 5.11 Modes of failure after 14 days for 5 mm thick 12 % sodium silicate coarse clay mortar joints with and without plant-fibres in stacks of perforated brick units cut from perforated 1.89 % wood-fibre block units a) and b) showing failure of the joint through the brick units for the mortar without plant-fibre and showing failure through the mortar joints for the mortars containing c) 1 % straw and d) 1 % flax

The failure through the joints was due to the wetness of the coarse clay mortars after 14 days which in effect gave the mortar a lower strength than that of the bond and brick units. This indicates that the 5 mm coarse clay mortar joints require longer drying out times to develop their ultimate strengths than the 3 mm fine clay mortar joints applied with the trowel, which were significantly drier at 14 days (refer to Chapter 4, section 4.3.3), and the 3 mm or thinner dipped or scoop applied joints. It is speculated that after 28 days the strengths of the coarse clay mortars would improve and be comparable to those of the 3 mm thick trowel and dipped applied fine clay mortars at 28 days. The slower drying rate of the 5 mm thick coarse clay mortars were related to the thicker joints, nature of the mortar and higher moisture contents of the masonry units due to their high wood-fibre contents (1.89 %).

The mortar bond strengths of the joints at 14 days do however indicate that the 5 mm thick joints prepared with the 12 % sodium silicate mortars containing the coarse brick clay and plant-fibres were suitable for the construction of thin-walls. Mortar bond strengths of all the joints tested were significantly higher than the 0.20 N/mm^2 required after 14 days except for one of the joints from the mortar containing the chopped flax. At 28 days the joint would have dried out sufficiently to exceed the bond strength required for thin-wall construction.

5.5.2 Compressive strength of masonry

Compressive strengths and stiffness of the masonry were determined on wall panels constructed from the solid, perforated and wood-fibre block and half-block sized masonry units (BS EN 1052-1:1999). Owing to the size of the blocks the wall panels required for testing were two blocks wide and three blocks high (i.e. 510 mm × 122 mm × 765 mm – Figure 5.12). The scoop method was used to apply the mortar to the solid block units and the dipping method to the perforated block units. No mortar was applied to the perpendiculars.

Figure 5.12 Compressive strength tests of wall panels showing modes of failure for a) automatic and b) manual loading methods

Wall panels were conditioned for 28 days at 20 ° C and 60 % - 65 % RH. Wall panels were capped with dental plaster prior to testing to ensure a smooth surface required for even loading. Two methods of loading (i.e. automatic and manual) were used to determine the compressive strengths of the wall panels owing to problems associated with the static materials test machine (Figure 5.12). Wall panels were automatically loaded at a constant rate of 0.5 mm/min to allow failure after 15 minutes (BS EN 1052-1:1999). The manual load rate varied but the wall panels were loaded at rates to ensure failure after 15 minutes. The change in height or displacement of the wall panels with time (i.e. while applying force) was recorded to calculate the modulus of elasticity (i.e. Young's modulus), which is a measure of stiffness of the wall panels.

Compressive strength (average of three determinations) of the solid block wall panels without wood-fibre (1.90 N/mm^2) was higher than the gross compressive strength but similar to the net compressive strength of the perforated wood-fibre block wall panels (1.40 N/mm^2 and 1.87 N/mm^2 respectively). Gross and net compressive strengths of the perforated block wall panels without wood-fibre (0.89 N/mm^2 and 1.20 N/mm^2 respectively) were substantially lower than those with wood-fibre (Table 5.6). Stiffness (average of three determinations) of the perforated block wall panels without wood-fibre (2679 N/mm^2) was higher than that of the solid block wall panels without wood-fibre (2136 N/mm^2) and that of the perforated wood-fibre block wall panels (1502 N/mm^2) (Table 5.6). Modes of failure were all through the masonry units and not through the mortar (Figure 5.12).

Table 5.6 Compressive strength and stiffness of solid, perforated and perforated wood-fibre wall panels conditioned at 22 °C and 60 % - 65 % RH for 28 days

Wall panel type and test method	Gross strength (N/mm^2)	Net strength (N/mm^2)	Young's modulus (N/mm^2)
Solid 1 - auto	2.12	2.12	1814
Solid 2 - auto	1.86	1.86	1181
Solid 3 - manual	1.72	1.72	3412
Solid mean	**1.90**	**1.90**	**2136**
Perforated 1 - auto	1.14	1.52	1739
Perforated 2 - manual	0.81	1.10	2335
Perforated 3 - manual	0.72	0.98	3962
Perforated mean	**0.89**	**1.20**	**2679**
Wood-fibre 1 - auto	1.59	2.12	1252
Wood-fibre 2 - manual	1.11	1.50	1917
Wood-fibre 3 - auto	1.49	1.98	1337
Wood- fibre mean	**1.40**	**1.87**	**1502**

Characteristic compressive strengths calculated from the gross compressive strengths for the solid block panels (1.59 N/mm^2) and perforated wood-fibre block panels (1.12 N/mm^2) were higher than that required for low strength masonry materials (1.10 N/mm^2) such as aerated concrete block (1.40 N/mm^2) using a thin-bed mortar (BS EN 1996-3:2006 and BS EN (NA) 1996-3:2006), that is the solid block and perforated wood-fibre block masonry systems were suitable for the construction of 100 mm thick non-load bearing walls. Characteristic compressive strength of the perforated block panels without wood-fibre (0.73 N/mm^2) was substantially lower than that required and not suitable for construction of thin walls.

Wood-fibre substantially improved the compressive strength of unfired clay masonry and substantially reduces the stiffness. Compressive strength of the perforated wood-fibre block panels was 40 % higher and stiffness 20 % lower than that of the perforated block panels without wood-fibre. The lower stiffness was possibly due to the lower stiffness of the wood-fibre which gave a lower composite stiffness. This stiffness reduction should be considered along with the significantly improved the toughness of the unfired clay masonry when wood fibre is added. The thin-joint mortar developed from the unfired clay containing 12 % sodium silicate gave the strength and bond strengths required for thin-wall construction.

Compressive strength measured using the manual method was significantly lower and stiffness significantly higher than that measured using the automatic or static test machine method. The differences in the compressive strengths and stiffness measured using the two methods are not fully understood. The only differences in the test procedure was the variable loading rate used in the manual method as opposed to the constant loading rate in the automatic test method. If the lower compressive strength values for the manual test are taken into account the average and characteristic compressive strengths for the perforated block panels without wood-fibre in particular could have been significantly higher and give a characteristic compressive strength similar to that required for construction of thin-walls using low strength materials and a thin mortar joint.

Thicker mortar joints were necessary to compensate for the poor tolerances of the block sized unit. It is speculated that with better tolerances or thicker mortar joints to compensate for the poor tolerances and mortared perpendiculars the wall panels would have acted more like a monolithic structure and given higher compressive strengths.

5.5.3 Flexural strength

Flexural strengths were determined on wall panels constructed from the solid, perforated and wood-fibre block and half-block sized masonry units (BS EN 1052-2:1999). Flexural strengths were determined for two principal axes of loading (i.e. four-point loading with the load applied parallel to the bed joints and four-point loading with the load applied perpendicular to the bed joints). Owing to the size of the blocks the wall panels required for testing when loaded parallel to the bed joints were two blocks wide and five blocks high (i.e. 510 mm × 122 mm × 1275 mm – Figure 5.13) and those required for testing when loaded perpendicular to the bed joints were three blocks wide and three blocks high (i.e. 765 mm × 122 mm × 765 mm – Figure 5.14).

The scoop method was used to apply the mortar to the solid block units and the dipping method to the perforated block units. No mortar was applied to the perpendiculars. Wall panels were conditioned for 28 days at 20° C and 60 % - 65 % RH prior to testing. A load rate of approximately 0.03 N/mm^2/min was applied manually until failure for both the tests parallel and perpendicular to the bed joints (BS EN 1052-2:1999).

Average and characteristic flexural strengths when loaded in the direction parallel to the horizontal bed joints (average of five determinations) of the solid block wall panels without wood-fibre (0.40 N/mm^2 and 0.27 N/mm^2 respectively) were similar to those of the perforated wood-fibre block wall panels (0.42 N/mm^2 and 0.28 N/mm^2 respectively) whereas those of the perforated block wall panels without wood-fibre (0.31 N/mm^2 and 0.20 N/mm^2 respectively) were significantly lower (Table 5.7). Cracks were evident in masonry units within the two inner points of loading but the modes of failure were predominantly through the masonry units delaminating onto either of the two horizontal mortar bed-joints within the two inner points of loading (Figure 5.15).

Figure 5.13 Set-up of manual test rig to determine flexural strengths parallel to bed joints of wall panels constructed two blocks wide and five blocks high (i.e. 510 mm × 122 mm × 1275 mm)

Figure 5.14 Set-up of manual test rig to determine flexural strengths perpendicular to bed joints of wall panels constructed three blocks wide and three blocks high (i.e. 765 mm × 122 mm × 765 mm)

Average and characteristic flexural strengths when loaded in the direction perpendicular to the horizontal bed joints (average of five determinations) of the solid block wall panels without wood-fibre (0.22 N/mm^2 and 0.15 N/mm^2 respectively) were substantially higher than those of the perforated wood-fibre block wall panels (0.13 N/mm^2 and 0.09 N/mm^2 respectively) and those of the perforated block wall panels without wood-fibre (0.11 N/mm^2 and 0.07 N/mm^2 respectively) (Table 5.7). Modes of failure of all the wall panels tested were directly through the either of the two adjacent block units positioned between the inner loading points in the centre row of the wall panel (Figure 5.16).

Figure 5.15 Modes of failure of wall panels for horizontal bed-joints parallel to direction of four-point loading (a) failure initiating in block, (b) failure initiating in block unit at mortar bond interface, (c) failure of solid block units onto scoop applied mortar and (d) failure of perforated block units onto dip applied mortar

Figure 5.16 Mode of failure of wall panels for horizontal bed-joints perpendicular to direction of four-point loading showing failure in block units positioned between inner loading points

The flexural strengths of the wall panels measured parallel to the bed joints were substantially higher than those measured perpendicular to the bed joints.

Flexural strengths of the solid block panels without wood-fibre parallel to the bed joints was double those perpendicular to the bed joints whereas the flexural strengths of the perforated block panels with and without wood-fibre parallel to the bed joints were three times higher than those perpendicular to the bed joints (Table 5.7).

Table 5.7 Average and characteristic flexural strengths measured during four point loading in directions parallel and perpendicular to the horizontal bed joints of wall panels without mortared perpendiculars conditioned at 20 °C and 60 % - 65 % RH for 28 days

Wall panel	**Load Direction**	**Average strength** (N/mm^2)	**Characteristic strength** (N/mm^2)	**Standard deviation** (N/mm^2)
Solid	Parallel	0.41	0.27	0.08
	Perpendicular	0.22	0.15	0.03
Perforated	Parallel	0.31	0.20	0.04
	Perpendicular	0.11	0.07	0.01
Wood-fibre	Parallel	0.42	0.28	0.07
	Perpendicular	0.13	0.09	0.01

The higher flexural strengths of the solid block wall panels without wood-fibre than those of the perforated block wall panels without wood-fibre were due to the failures of the wall panels through the respective masonry units and the lower flexural strengths of the perforated block units without wood-fibre with perforations running perpendicular to or in the direction loading (i.e. block wrench 90° or block wrench 0° - Table 5.8) than those of the solid block units without wood-fibre (Table 5.8). The substantially lower flexural strength of the perforated block units with perforations in the direction of loading compared to that of the solid block units account for the more significant difference in flexural strengths between the solid and perforated block wall panels without wood-fibre when loaded perpendicular to the bed joints. The perforations run in the load direction when the wall panels were loaded perpendicular to the bed joints.

The higher flexural strengths of the perforated wood-fibre block panels compared to those of the perforated block panels without wood-fibre when loaded parallel to the bed joints were due to the substantial increase in flexural strength the wood-fibre gave to the perforated block units with the perforations running at 90° to the load direction (bond wrench 90° - Table 5.8). The wood-fibre gave no improvement in strength for the wall panels loaded perpendicular to the bed joints. This was due to a significantly lower improvement in flexural strength for perforated wood-fibre block units when perforations ran in the direction of loading (i.e. bond wrench 0° - Table 5.8) and more importantly the un-mortared perpendiculars in the wall panels.

The un-mortared perpendiculars account for the substantially lower flexural strengths of the wall panels loaded perpendicular to the bed joints than those loaded parallel to the bed joints. Mortaring the perpendicular joints may increase the flexural strength perpendicular to the bed joints. The wall panels with un-mortared perpendiculars required failure through only one block in a wall three blocks high (Figure 5.16), that is the area to which the load is applied is in effect reduced. The flexural strengths measured perpendicular to the bed joints of the wall panels with un-mortared perpendiculars could in effect increase to three times more if the perpendiculars in the wall panels were mortared and the mortar was fully bonded to the bricks. For example, bond strengths in the perpendiculars of at least half that obtained in the bed joints doubles the flexural strength perpendicular to the bed joints. The perpendicular joints need to be pinned down to prevent them from opening up at the back of the wall when in tension. As a result, improving the strength of the perforated block units will therefore not give a noticeable improvement in flexural strength of the wall panel with un-mortared perpendiculars loaded perpendicular to the bed joints.

Table 5.8 Comparison of average and characteristic flexural strengths measured during four-point loading of masonry to bending strengths of block units measured using the bond wrench test method and bond strengths of joints in brick unit stacks measured using the bond wrench test method

Wall panel	**Test Methods**	**Average strength** (N/mm^2)	**Characteristic strength** (N/mm^2)	**Standard deviation** (N/mm^2)
Solid	Wall panel parallel	0.41	0.27	0.08
	Block wrench 90°	0.54	0.42	0.06
	Stack wrench	0.39	0.28	0.07
	Wall panel perpendicular	0.22	0.15	0.03
	Block wrench 0°	0.51	0.23	0.20
Perforated	Wall panel parallel	0.31	0.20	0.04
	Block wrench 90°	0.39	0.27	0.06
	Stack wrench	0.39	0.23	0.09
	Wall panel perpendicular	0.11	0.07	0.01
	Block wrench 0°	0.18	0.03	0.10
Wood-fibre	Wall panel parallel	0.42	0.28	0.07
	Block wrench 90°	0.84	0.56	0.15
	Stack wrench < 3 mm	0.31	0.11	0.16
	Stack wrench = 3 mm	0.58	0.40	0.10
	Wall panel perpendicular	0.13	0.09	0.01
	Block wrench 0°	0.31	0.25	0.03

The failure of the panels at the interface of the bed joints due to the brick breaking onto the mortar (Figure 5.15) indicated that the flexural strength and bond strength of the 12 % sodium silicate mortar were either similar to or higher than the flexural strength of the masonry units. The absence of failure directly through the block units was due to the application of the mortar. The mortar was applied similar to what would be expected on-site using thin-joint scoop and dipping methods. The objectives were to evaluate the use of thin-joint mortar application techniques and the performance of the unfired clay masonry with thin horizontal bed-joints. Joints were less than the 3 mm required to compensate for poor tolerances and surface irregularities of the masonry units. Coverage of the masonry units was not as thorough as that obtained when using the trowel application method. Areas of poor bonding resulted between the mortar and masonry units, which acted as stress raisers during loading. Cracks initiated and propagated in the masonry units above the bond interface giving the failure surfaces observed (Figure 5.15).

The flexural strengths of the wall panels loaded parallel to the horizontal bed joints were similar to the bond strengths of the brick stacks due to the similar mortar application methods and failure modes (Table 5.8) with the exception of the stacks made using the wood-fibre perforated brick units, which gave lower bond strengths with the similar thin-joint application methods but substantially higher with the dipping method ensuring a 3 mm thick bond to compensate for poor tolerances and irregularities.

Characteristic flexural strengths of the wall panels measured when loaded parallel to the horizontal bed joints were acceptable for the construction of non-load bearing thin-walls. Gross flexural strengths of all the wall panels tested were higher than the 0.20 N/mm^2 required in this direction (BS EN (NA) 1996-3:2006 - Eurocode 6) and failures were all within the inner two loading points. Characteristic flexural strengths of the wall panels measured when loaded perpendicular to the bed joints were unacceptable for the construction of non-load bearing thin-walls. Gross flexural strengths of all the wall panels tested were substantially lower than the 0.4 N/mm^2 required in this direction (BS EN (NA) 1996-3:2006 - Eurocode 6). The flexural strengths of the solid block wall panels without wood-fibre ranged from 0.19 N/mm^2 to 0.26 N/mm^2, those of the perforated block panels without wood-fibre from 0.11 N/mm^2 to 0.13 N/mm^2 and those of the perforated wood-fibre block panels from 0.14 N/mm^2 to 0.15 N/mm^2.

A further series of five wall panels were constructed using the perforated wood-fibre blocks with mortared perpendiculars to determine the improvement in flexural strengths when loaded in the direction perpendicular to the horizontal bed-joints. Mortar was applied to the horizontal bedding surfaces using the dipping method and to the perpendicular surfaces using the special scoop. Joints thicknesses were adjusted using a trowel where necessary to compensate for the poor tolerances of the block units and give sound well-organised wall panels (Figure 5.17). Wall panels were conditioned at 20 °C and 60 % - 65 % RH for 28 days prior to testing.

Average and characteristic flexural strengths (average of five determinations) of the wall panels with mortared perpendiculars (0.33 N/mm^2 and 0.22 N/mm^2 respectively) were almost three times higher than those of the wall panels with un-mortared perpendiculars (0.33 N/mm^2 and 0.22 N/mm^2 respectively) (Table 5.9). Modes of failure in the top and bottom courses were either through the block units delaminating onto the perpendicular mortar joints or directly through the block units in the area directly adjacent to the perpendicular mortar joints positioned within the inner loading points (Figure 5.17) and followed a line directly through the centre of the block units positioned in the middle of the wall panels between the two inner loading points.

Mortaring the perpendiculars gave lower but more comparable flexural strengths measured perpendicular to the horizontal bed-joints than those measured parallel to the horizontal bed-joints (Table 5.9). The lower flexural strengths were directly related to the orientation of the perforations in the block units when tested, i.e. the lower flexural strengths of the perforated wood-fibre block units when measured in the direction of extrusion (bond wrench 0° - Table 5.8) compared to those measured in the direction perpendicular to the direction of extrusion (bond wrench 90° - Table 5.8). The scoop method of application failed to give a mortar joint that covered the entire perpendicular surfaces of the block units (Figure 5.17d), which potentially lowers the flexural strength of the wall panels perpendicular to the horizontal bed-joints.

Figure 5.17 Wall panels constructed of perforated wood-fibre block units with mortared perpendiculars (a) appearance of wall panel with mortared perpendiculars, (b) and (c) failures of wall panels with mortared perpendiculars when loaded at four points perpendicular to the horizontal bed joints, and (d) and (e) failure surfaces of wall panels with mortared perpendiculars when loaded at four points perpendicular to the horizontal bed joints

Table 5.9 Average and characteristic flexural strengths measured during four point loading in directions perpendicular to the horizontal bed joints of perforated wood-fibre wall panels with and without mortared perpendiculars conditioned at 22 °C and 60 % RH for 28 days

Wall panel	**Average strength** (N/mm^2)	**Characteristic strength** (N/mm^2)	**Standard deviation** (N/mm^2)
Perpendicular with mortared perps	0.33	0.22	0.01
Perpendicular with un-mortared perps	0.13	0.09	0.01
Parallel with un-mortared perps	0.42	0.28	0.07

Mortaring the perpendiculars failed to give the characteristic flexural strength of 0.40 N/mm^2 required for the perforated wood-fibre block wall panels when loaded in the direction perpendicular to the bed-joints (BS EN (NA) 1996-3:2006 - Eurocode 6). All the wall panes tested gave flexural strengths lower than the 0.40 N/mm^2 required. It is speculated that with good brick-laying practice and using a trowel to ensure 3 mm thick horizontal and perpendicular mortar joints that covers the entire bedding surfaces of the masonry units that a substantial improvement in the flexural strengths can be obtained such as that seen with the wood-fibre brick unit stacks (Table 5.8). However, the criteria governing flexural strength in the direction perpendicular to the bed-joints is the strengths of the perforated masonry units in this direction and these need to be improved to ensure the required flexural strengths of the wall panels in the direction perpendicular to the horizontal bed joints.

5.5.4 Initial shear strength of horizontal mortar bed joints in masonry

The initial shear strengths of the horizontal bed joints were not successfully determined. On loading the stacks prepared (i.e. block units sliced into three and mortared together to give two horizontal bed-joints – Figure 5.18a) the failures were all through the crushing or splitting of the cut brick sized units in the stacks. According to the standard test method (BS EN 1052-3:2002) shear failures within the masonry units (Figure 5.18e) or the crushing or splitting failures in the masonry units (Figure 5.18f) render the test result null and void. A valid failure is either shear failure in the mortar (Figure 5.18d) or shear failure in the masonry unit/mortar area (i.e. either on one of the two faces of the masonry units - Figure 5.18b or divided between the two faces of the masonry units - Figure 5.18c).

The initial shear values recorded for the solid block unit stacks tested were 0.32 N/mm^2 and 0.38 N/mm^2, which were higher than the 0.30 N/mm^2 required for the construction of walls using low strength materials (BS EN (NA) 1996-1-1:2005)

5.6 Extrusion of wood-fibre masonry units

The tests on the prototype unfired clay blocks produced concluded that the wood-fibre gave improvement in the properties of the unfired clay (i.e. brick clay 2). The wood-fibre significantly improved the flexural strength and toughness of the unfired clay masonry units and the masonry constructed using the unfired clay blocks and a 12 % sodium silicate mortar developed from the respective brick clay. Attaining the desired format for unfired clay masonry units to construct thin non-load bearing walls required another series of unfired clay masonry units to qualitatively assess the properties of the unfired clay masonry with and without wood-fibre and the development of further prototype unfired clay block formats which would be used to conduct tests (i.e. standard and modified tests required for masonry units and assessing the behaviour of the units in real situations).

Numerous problems needed to be overcome to produce another series of unfired clay masonry units with and without wood-fibre successfully. The most important of which was the integration of the wood-fibre into the clay brick manufacturing process. A correct procedure to add and mix the wood-fibre into the clay is essential to ensure a homogeneous clay/wood-fibre mixture is obtained. Such a mixture must then be tempered to give the desired plasticity for extrusion during the final mixing stage in the pug mills (i.e. after mixing the clay and wood-fibre needs to normalised so that they are in equilibrium with each other). A homogenous and well tempered mixture will make the extrusion of stiff green masonry units with good strengths to resist deformation and the desired wood-fibre contents possible.

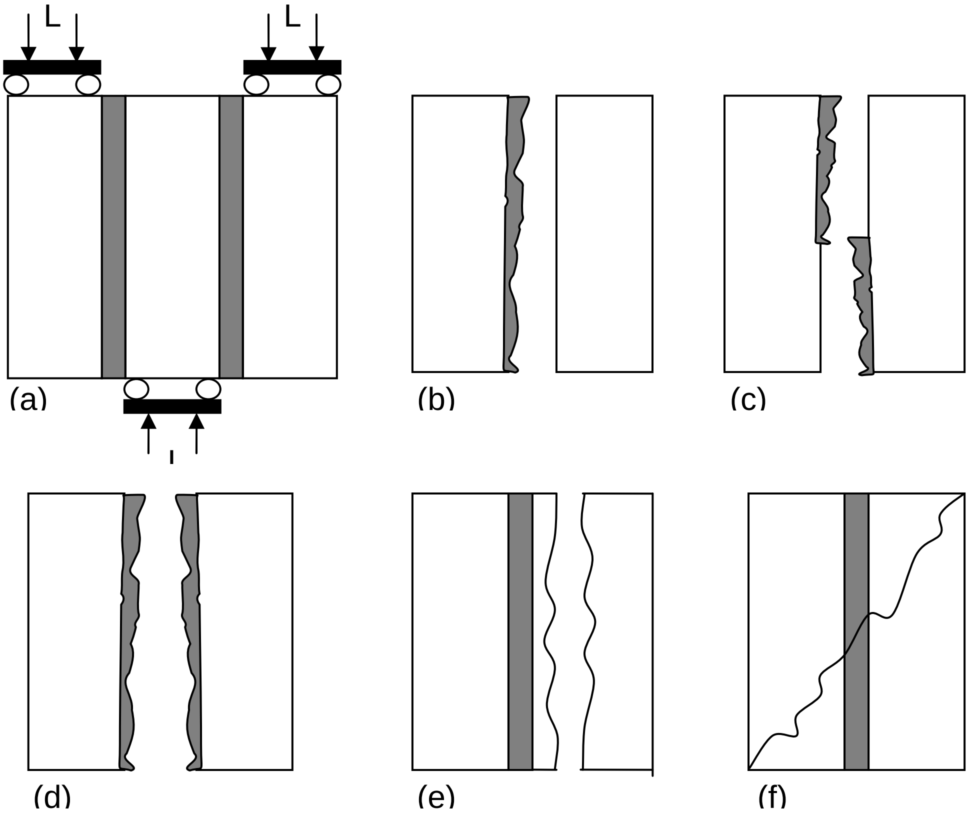

Figure 5.18 Types of failure allowed or not allowed for initial shear strength tests of horizontal bed joints (a) loading of stack prepared from cut block sized units, (b) and (c) shear failure in the unit/mortar bond area either on one or divided between two unit faces, (d) shear failure only in the mortar, (e) shear failure in the unit and (e) crushing and or splitting failure in the units

This section documents the outcomes of an investigation into the manner in which a homogeneous clay/wood-fibre mixture suitable for the extrusion of unfired clay block sized masonry units was obtained using brick clay 2 and discusses the extrusion of the wood-fibre unfired clay block units.

5.6.1 Clay and wood-fibre mixture for extrusion

A homogenous clay and wood-fibre mixture was desired which would give the desired plasticity for the extrusion of green masonry units of good strengths and tolerances. A good mixing stage was required to ensure the bulky wood-fibre material (Figure 5.19) could be mixed into the brick clay to give a homogeneous mixture. After mixing the mixture required tempering or souring to ensure the clay and the wood-fibre attained the equilibrium moisture content. Souring is the term used in the brick industry whereby clay sourced directly from the quarry is left to weather in a stockpile to attain the desired properties for the eventual extrusion of unfired clay bricks.

An investigation into the manner in which the wood-fibre could be mixed into the brick clay and the effect of the wood-fibre on the plasticity of the clay was conducted in the laboratory. A pan-mixer was used in the investigation to mix the wood-fibre into the clay and water into the clay mixture to give desired plasticity for souring or extrusion. Clay and wood-fibre mixtures were successfully prepared using the pan-mixer in a previous investigation (Chapter 3, section 3.5).

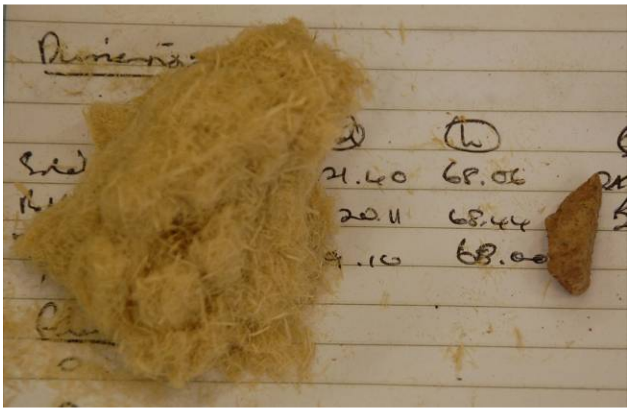

Figure 5.19 Bulkiness of wood-fibre approximately 10 g of wood-fibre (left) and unfired brick clay 2 (right)

A number of clay mixtures with and without wood-fibre were prepared using brick clay 2 and the growing medium wood-fibre (GMF). Brick clay 2 was sourced directly from the factory after the grinding stage (approximately 5 % moisture content) and the GMF was obtained in growth bags (approximately 16 % moisture content). Approximately 10 kg mixtures were prepared at a time. Wood-fibre at 2 % by weight was added to the clay and mixed. After 10 minutes of mixing the wood-fibre was successfully fluffed out and dispersed into the clay. Water was added to attain the desired plasticity for souring or extrusion. Plasticity of the clay mixtures was assessed by observing when the cracks appeared on squashing a 20 cm ball and on a sausage 10 mm in diameter when squeezed between the thumbs. The plasticity could not be assessed by rolling a 3 mm thread, which is common practice, owing to the fibre restricting the breakages in the thread.

A clay mixture without wood-fibre close to its plastic (approximately 17 % water content by weight) such as that used for the extrusion of the masonry units was prepared. On mixing the wood-fibre into the wet clay mixture the plasticity drastically changed. The clay was no longer workable and became crumbly and unsuitable for extrusion. Increasing the water content by approximately 4 % regained the original workability (i.e. plasticity of the clay suitable for extrusion). Allowing the non-plastic clay/wood-fibre mixture to sour gave a mixture with suitable plasticity for extrusion after 36 hours.

A number of different mixing regimes were investigated. The wood-fibre was moistened with the amount of water required to give the clay the desired plasticity for extrusion. This wet wood-fibre was easier to mix into the clay as sourced and gave better workability than when the wood-fibre as sourced was mixed into moistened clay. Souring the former mixture to attain the plasticity desired for extrusion took 24 hours instead of 36 hours. However, mixing the wood-fibre as sourced into the clay as sourced and then adding the water to attain the desired plasticity was easier. This method was used to prepare mixtures containing lower water contents than that required to give the desired plasticity for extrusion (i.e. 13 % and 15 %). The mixtures with wood-fibre took longer times to sour (48 hours at least) to reach similar plasticity as those without the wood-fibre but were easier to handle as the mixtures could be fed into the production process using a conveyor whereas the soured plastic mixtures could not. Water contents of the slightly drier mixtures could be adjusted at the extruder to give the desired plasticity for extrusion.

Souring the clay/wood-fibre mixture is therefore essential to ensure the clay and wood-fibre reaches the equilibrium moisture content of the mixture. Souring mixtures at water contents below that required for extrusion is advisable to prevent the mixture from coagulating and becoming plastic. Once plastic the mixtures are difficult to feed and cannot be stored in silos.

5.6.2 Extrusion trial

A trial was planned to extrude unfired clay masonry units containing wood-fibre. Approximately five tonnes of brick clay 2 was sourced from the factory directly after grinding. Wood-fibre (GMF) at 2 % by weight was mixed into the clay in the laboratory using two pan mixers with a 200 kg capacity. Water was added to obtain a mixture with a water content of 13 % to 15 % (i.e. below that require for extrusion). The mixture was intended to sour for 48 hours in one tonne tote bags that were sealed to prevent drying out. Owing to problems at the factory the mixture was left to sour for 7 days instead.

The soured clay/wood-fibre mixture was fed onto a conveyor directly into the pug mills at the extruder, effectively bypassing the silo where problems existed on the previous trial. Water was adjusted to achieve the desired plasticity for extrusion and approximately three-hundred solid unfired clay block masonry units (220 mm × 215 mm × 100 mm) containing 2 % wood-fibre were extruded. The block units were then stacked on drying racks and dried in the oven at 100 °C for 48 hours. The block units were then taken on-site to build the inner-leaf wall of an extension to a domestic dwelling. A 12 % sodium silicate mortar developed from the brick clay 2 sourced directly from the factory after grinding (i.e. in its un-ground state) and fine builders sand (i.e. (1 part clay to 3 parts sand) was used to construct the wall. A 5 mm joint was used to compensate for the tolerances of the block units and to optimise the flexural strength and toughness of the wall. The mortar was applied using a trowel. The perpendiculars of the wall were mortared to give the wall the desired flexural strength perpendicular to the bed-joints. The unfired clay wall was constructed on top of a row of standard low strength concrete block units (440 mm × 215 mm × 100 mm) and rendered with a lime plaster to protect the wall from water damage.

No major problems were experienced with the trial. Mixing of the wood-fibre into the clay was successful. The wood-fibre easily dispersed throughout the clay and a homogenous mixture was obtained. On feeding the mixture onto the conveyor it was evident that the souring time was too long as the mixture had started to form lumps of clay that needed to be dug out of the tote bag. Adjusting the water to achieve the desired plasticity for extrusion was easy and a good stiff column of clay was extruded without any stoppages or abnormal problems. Wire-cutting the solid extruded column of clay with the longer fibre lengths (i.e. GMF 20 mm lengths as opposed to 10 mm length for the MDF) gave no problems. No shrinkage cracks were evident on drying.

Tests were not conducted on the masonry units. The masonry units were produced to ascertain whether or not it was possible to extrude sound and consistent unfired clay block units containing wood-fibre without any problems (i.e. without any blockages or stoppages). Tolerances of the block units were significantly better than before. Construction of the wall presented no major problems and the 5 mm joint was more than sufficient to overcome the tolerances of the block units and attain a well-organised wall.

5.7 General discussion

Some good results were obtained from the tests conducted on the unfired clay masonry and masonry units. The only qualitative results however were those obtained for the solid and perforated masonry units and masonry without wood-fibre as no problems were experienced with the extrusion of these units. The extrusion of the perforated wood-fibre masonry units was marred with problems. The poor mixing of the wood-fibre into the clay resulted in a significant variation in the wood-fibre content between the different sizes of masonry units extruded. Variation of the wood-fibre was not confined to the different unit sizes alone but also occurred within the units of each size extruded. The variation in wood-fibre content throughout the clay mixture and the high moisture demand of the wood-fibre made extrusion difficult. The water to give the desired plasticity for extrusion required constant adjustment and ultimately resulted in green masonry units that were either to dry or to wet.

Although the standard test procedures are essential in the development of a material suitable for mainstream construction a number of meaningful results were obtained from observations and rudimentary test procedures such as the drop and water erosion tests to assess the toughness and durability of the material. Some interesting observations were also made when working with the materials to determine their suitability in construction. Wall panels were constructed with corners to determine the plastering and rendering of the unfired clay materials and screw fixing strengths.

On sawing the material with a standard wood-saw or alligator power saw using a masonry blade the perforated wood-fibre block units gave much cleaner cuts compared to that of the solid and perforated block units without wood-fibre and resisted cracking. Screwing self tapping screws (8 mm diameter) into the perforated wood-fibre block was easier and the material failed to crack and strip. The pull-out loads of screws inserted via standard plugs into the solid masonry units were higher than those inserted into the perforated masonry units with and without wood-fibre (2.0 kN compared to 0.6 kN and 0.4 kN respectively). The lower pull-out loads were related to the perforations in the masonry units. A lime render and a clay plaster were successfully applied to the unfired clay masonry. The plasters were applied over a glass fibre mesh which was ripped away by hand after the plasters had dried. The plasters adhered well to the surface of the unfired clay masonry.

5.8 Conclusions

The unfired clay masonry and the unfired clay masonry units gave good properties. Compressive strengths and flexural strengths of the unfired clay masonry units and the compressive strengths, and flexural strengths parallel to the horizontal bed-joints of the unfired clay masonry, with the exception of the flexural strengths of the unfired clay masonry measured in the direction perpendicular to the horizontal bed-joints, were similar or higher than those required for the construction of thin non-load bearing walls and comparable to those of low strength materials such as aerated concrete. Bond strengths of the horizontal bed joints were all suitable for the construction of thin non-load bearing walls.

The poor flexural strengths perpendicular to the bed-joints rendered the masonry unsuitable for the construction of thin non-load bearing walls. The poor flexural strengths perpendicular to the bed-joints were directly related to the un-mortared perpendiculars. Mortaring of the perpendiculars substantially improved the flexural strength of the masonry perpendicular to the bed-joints. The improvement in flexural strength was not sufficient to overcome the poor flexural strengths of the perforated masonry units when loaded in this direction but would give the solid units without wood-fibre the flexural strength required for construction when loaded in this direction.

Wood-fibre substantially improved the properties of the unfired clay material. Gross compressive strengths of the perforated masonry formats and gross flexural strengths of the perforated masonry and masonry unit formats with the exception of the flexural strength perpendicular to the bed-joints of the masonry were substantially higher with the wood-fibre than without and either similar to or higher than those of the solid masonry and masonry unit formats without wood-fibre. A lighter, tougher and stronger perforated unfired clay masonry unit with more value than the dense and heavy solid unfired can be produced which reduces breakages during transport and handling, resists internal stresses that develop with the absorption of moisture namely during the mortaring and plastering of thin walls, improves screw fixing strengths and resistance to abrasion and water erosion.

Bond strengths and modes of failure indicated that the unfired clay mortar developed from finely ground brick clay 2 and fine builders sand (i.e. 1 part clay to 3 parts sand) containing 12 % sodium silicate gave strengths and bond strengths suitable for the construction of thin non-load bearing walls. The scoop and dipping application methods gave mortar joints of the required strengths but were not suited for the application of a 3 mm thick joint which covered the entire surface of the masonry units. A 3 mm thick joint is required to compensate for the tolerances expected in standard extruded masonry units (± 2 mm). The low viscosity of the mixtures and the weight of the masonry units gave joints between 1 mm and 2 mm thick and due to the poor tolerances of the masonry units resulted in areas of poor bonding giving premature failures in the masonry units directly above the mortar bond. A thicker joint covering the entire surface of the masonry unit would minimise areas of poor bonding and give more failures directly through the masonry units optimising the strength of the unfired masonry.

A premix and souring stage to integrate the wood-fibre into the clay brick extrusion process was successful. A clay mixture containing 2 % wood-fibre which was allowed to sour was successfully extruded. Unfired clay masonry units of good wet strengths were extruded without any problems. The tolerances of the masonry units were good and suitable for the construction of masonry using a 3 mm thick joint.

A further trial is required to develop a series of prototype blocks to qualitatively assess the properties of solid and perforated unfired clay masonry units with and without wood-fibre. Shape and size of the perforations should be altered to attain the required flexural strengths perpendicular to the bed-joints for the perforated wood-fibre masonry units. A thicker mortar joint (i.e. 5 mm) should be used to compensate for tolerances and surface irregularities of the masonry units, and to allow for the addition of straw to the mortar to reduce wastage down the perforations and use of the coarser brick clay sourced directly from the factory in the manufacture of the mortar.

The increase in cost of the thicker mortar joint (i.e. from 7.2 pence per metre to 12 pence per metre) would be offset by the saving in cost when adding straw to the mortar to reduce wastage down perforations and from the use of the coarse brick clay sourced directly from the factory in the manufacture of the unfired clay mortar. Cost for the 5 mm thick joint is double that of the standard cement mortar 10 mm thick joint (6 pence per metre) but embodied carbon is substantially lower (0.07 kg.CO_2 per metre compared to 0.4 kg.CO_2 per metre). The added advantages and robustness of the thicker 12 % sodium silicate mortar joint content makes the increase in cost and embodied carbon (0.04 kg.CO_2 per metre compared to 0.07 kg.CO_2 per metre) less significant.

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CHAPTER 6

CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

6.1 Introduction

The lack of appropriate specifications, building standards and regulations hinders the use of earth in most countries. In developed countries it is also the substantially higher cost of labour and time associated with traditional forms of earth building that makes earth less favourable in modern mainstream construction. Although a number of design guidelines based on empirical evidence exist, many are limited due to a lack of scientific data. Earth has, however, gained recognition in modern construction due to its favourable environmental performance.

A few areas need to be addressed to further develop earth building as a mainstream building technology in developed countries. A need for education and training are essential for architects, builders, engineers and trades people. Mechanisation of the production and construction is required to reduce labour input and speed up the process to make earth building more competitive. Care must be taken not to unduly compromise the environmental benefits. A greater degree of component standardisation will be required to achieve this. Quality control in earth building and how to measure it reliably needs to be addressed.

This research, which was to develop an unfired clay masonry system suitable for the mainstream construction of thin non-load bearing inner walls, aimed to provide a foundation with which to develop earth as a material with the necessary specifications, standards and regulations demanded for a building material in modern mainstream construction. Industrially extruded unfired clay masonry units and mortars made from standard brick clays were most suited to achieve the aims and objective of the research. Brick clays used to extrude fired-clay brick units conform to strict specifications and standards. Quality control for the mixing of the brick clays and extrusion of the respective clay masonry units are good. Extruded unfired clay masonry units and mortars developed from the respective brick clays are therefore consistent and easily standardised to conform to specifications, standards and building guidelines and regulations required for the use of unfired clay masonry units and mortars in mainstream construction.

The research only focussed on the construction of non-load bearing inner walls due to the low strength and poor water resistance of the unfired clay materials. Improving the properties of the unfired clay materials to allow use in load bearing and exterior walls was beyond the scope of the research. The research does, however, provide a foundation for future research to develop the unfired clay into a more robust and durable building material for the construction of modern buildings.

The objective of this chapter is to document the conclusions and limitations of the research and to discuss the future work required to promote the use of the unfired clay masonry system in modern mainstream construction. The aim is to show that an unfired clay masonry system is suited to the construction of thin non-load bearing walls and that specification and standards can be formulated to disseminate the use of an unfired clay masonry system in modern mainstream construction. The scope of the chapter is to:

- illustrate the need for an unfired clay masonry system in mainstream construction
- show suitability of extruded unfired clay masonry units and unfired clay mortars in the construction of thin non-load bearing walls
- show that the unfired clay masonry is suitable for the construction of thin non-load bearing walls
- propose a procedure to produce the unfired clay masonry units and unfired clay mortar for mainstream construction
- account for the limitations encountered during the research
- advise on future research requirements to produce suitable unfired clay masonry units and unfired clay mortars for mainstream construction of modern buildings

6.2 Literature review

A good foundation from which to conduct the research was obtained from the literature review which included information gained from discussions, conferences and site-visits. Soil was defined in terms of classification, properties and phases. Standard laboratory and traditional field test procedures to identify soil for construction were documented and discussed. Construction techniques to ensure good traditional earth buildings were discussed and the use of earth in modern builds and mainstream construction was identified. Modern buildings and traditional buildings were compared and the importance of sustainable buildings in modern construction was discussed. The advantages and disadvantages of earth as a construction material were documented and discussed in particular the health and environmental benefits of buildings constructed with earth materials. Specifications and standards of relevance to the research in particular those applying to masonry construction were discussed. The clay brick extrusion process was described as the most appropriate manner in which to manufacture unfired clay blocks on a large enough scale to meet the demands of mainstream construction.

The literature review concludes that earth is still regarded as a traditional building material but that it can be adapted for use in mainstream construction, in particular as an unfired clay masonry system. A worldwide drive to establish earth as a modern construction material exists but in many countries it is still considered inferior to industrial buildings materials such as concrete and fired-clay brick. In less developed countries, concrete and fired-clay brick are favoured for the construction of domestic dwellings as earth is considered a building material used only by the poor. In developed countries, the low strength and poor durability of earth, and the higher costs and time required for the construction of modern buildings makes it undesirable for use. It is important to use earth in an appropriate manner so that the beneficial properties can be realised without placing the structure at risk.

Although earth has many health and environmental benefits it will continue to be considered inferior to these industrial building materials until it becomes recognised as a building material with specifications and standards to suit the guidelines and regulations demanded in modern mainstream construction. As a result, the research documented here is not only necessary but essential to the recognition of earth in modern construction.

6.3 Development of unfired clay masonry units

Unfired-clay brick units or green bricks, which are extruded but not fired as with standard fired-clay brick masonry units, are suitable for the construction of thin non-load bearing walls. All the extruded and oven-dried unfired-clay brick units sourced gave compressive strengths in excess of the 2.50 N/mm^2 at typical building humidity levels. This value is required for low strength materials used in the construction of non-load bearing walls. Compressive strengths are similar to that of standard aerated concrete blocks used in the construction of 100 mm thick inner leaf walls (i.e. 2.5 N/mm^2 – 3.5 N/mm^2). The unfired-clay brick units also gave flexural strengths substantially higher than the 0.20 N/mm^2 and 0.40 N/mm^2 required for walls constructed of low strength materials parallel and at right angles to the bed joints respectively.

Soils, i.e. the brick clays used for extrusion of the unfired-clay brick units, were all of similar properties. Soils were not technically classified as clays as they contained on average 25 % clay as opposed to 35 % clay, which be definition defines a clay soil. Soils are generally defined as clayey silt soils containing fine to coarse sand with traces of gravel and are of a low to intermediate plasticity. Such soils are ideal for the extrusion of stiff unfired clay-brick units. Quality control of the soil is good to ensure that the unfired-clay brick units produced give fired-clay bricks that confine to the specifications and standards required in modern construction. Compositions of the soils used do vary. Soils with higher clay contents generally give unfired-clay brick units of slightly higher strengths but increase shrinkage on drying.

Characteristics of the extruded unfired-clay brick units were studied to assist with the development and testing of an extruded prototype unfired-clay block unit. Capping was the most convenient method to determine the compressive strength. Grinding is time consuming and labour intensive. Compressive strengths can either be determined in the direction of extrusion or at right angles to the extrusion direction. Shape and size of the test specimens do not appear to affect compressive strength measurements and geometric factors used for fired clay masonry units need not be applied to normalise the measurements.

Compressive strengths of the unfired clay masonry units are significantly reduced by an increase in moisture content and the inclusion of perforations. The influence of moisture on compressive strength is critical. Walls are exposed to water during plastering, and risk exposure to water and high levels of relative humidity in domestic dwellings.

An increase in moisture content reduces the compressive strength of unfired clay masonry units. A sharp decrease in strength occurs from the oven dry state to that at ambient conditions where the moisture content stabilises at approximately 2 %. Compressive strengths of the unfired clay masonry units at moisture contents above 3 % are not suitable for the construction of non-load bearing walls. Water absorption during plastering and at a relative humidity above 90 % could increase moisture contents to above 3.00 %. Only the outer layers (10 mm to 20 mm) of unfired clay masonry units are affected by water absorption and they should still remain structurally sound in non-load bearing walls during plastering and at high relative humidity levels.

Perforations reduce the weight of the unfired clay masonry units which can improve handling and increase air and oven drying rates. Perforations in the direction of loading are likely to give acceptable strengths whereas perforations perpendicular to the direction of loading substantially lower the strength of the unfired clay masonry units making them unsuitable for the construction of walls. Larger size perforations reduce the compressive strength more than smaller size perforations occupying the same volume.

The inclusion of plant fibres improves the toughness, durability, drying rates, water transport properties, appearance and reduces the weight of the unfired clay brick units. The environmental benefits of using plant fibres are that carbon lock-up is achieved and that the unfired clay brick units remain recyclable and degradable. The perceived and actual increased performance also imparts more value to the unfired-clay masonry units. The main improvement is toughness as this improves the handling, transport and fixing properties and makes the unfired clay brick units more resilient to the inherent stresses developing in the unfired clay walls on plastering. Wood-fibre was demonstrated to be the best natural plant fibre tested. Compressive and flexural strength of the unfired clay specimens with wood fibre were not affected and the toughness of the specimens was significantly improved. Straw improved toughness but substantially reduced the compressive strength of the specimens. The disadvantages of using pant fibre is that it is expensive, decreases thermal mass, increases embodied energy, creates storage problems, is a potential fire risk hazard and hampers the production of the unfired clay masonry units.

Characteristics and properties of the clay masonry units assessed conclude that the brick clays and the industrial extrusion process used to manufacture the green brick units were suitable for the development of a prototype unfired clay block unit of dimensions similar to that of aerated concrete block (440 mm × 215 mm × 100 mm) used in the construction of inner leaf and non-load bearing walls. A brick-clay with “average” properties was chosen to develop the unfired clay block units. Such a brick-clay is more representative and once formulated the unfired clay block units could be produced at any factory or with any clay used for the extrusion of brick units. A brick-clay giving better performance was also not suited for trial purposes as the “Specials plant” (i.e. a low-capacity plant which could be used to manufacture non-standard units) was closed and the factory was only running a high-capacity main plant during the course of this project.

6.4 Development of an unfired clay mortar

Mortars developed from the clays used to manufacture the respective unfired clay brick units, which contain sufficient sand to minimise shrinkage on drying, are suitable for the construction of thin non-load bearing walls when sufficient sodium silicate is added. Thin mortar joints (± 3 mm) were found to be most cost effective. Sodium silicate contents in excess of 8 % gave bond strengths higher than the 0.2 N/mm^2 required for the construction of 100 mm thick walls. Strengths of these sodium silicate clay mortars and their respective bond strengths at 24 hours were adequate for construction. After 3 days the strengths of the mortars were close to maximum. Strengths appear to remain stable with time and no reduction in strength and bond strength of the sodium silicate mortars was observed after 3 years.

Strengths and bond strengths of 8 % sodium silicate mortars applied with a trowel to give 3 mm thick joints were either similar or stronger to the bending strengths of the brick units but were not as robust as the mortars with higher sodium silicate contents, namely 10 % and 12 %. At sodium silicate contents of 8 %, the mortar is notably dependant on composition, joint thickness, water content and method of application. Composition is important as there must be sufficient clay or fine particles to retain enough sodium silicate solution in the mortar for it to develop strength but not too much to restrict absorption of the sodium silicate across the interface into the unfired clay masonry units to develop good bond strength. Adding coarser clay or sand to the mortar mixture allows for more absorption of the sodium silicate solution into the masonry unit effectively reducing the sodium silicate content to below 8 %, which gives good bond strengths but inadequate mortar strengths and give premature failures of the joint through the mortar during bending.

A similar problem occurs at higher water contents such as those required for dipping or special tool application methods, which gave good mortar strengths and mortar bond strengths when using the 8 % sodium silicate mortar. Some lower than average bond strengths were, however, measured, which resulted in poor characteristic strengths. Application methods such as these generally give mortar joints thinner than 3 mm and owing to the high water content required for correct application the joints are easily compressed by the weights of the unfired clay block units resulting in joints of 1 mm thick. Bonding of the mortar to the unfired clay units with such thin joints or more precisely joints thinner than 3 mm are influenced by coarse particles in the mortar, surface irregularities and poor tolerances on the masonry units, which create dead spots that act as stress raisers during bending and results in the premature de-bonding of the mortar from the masonry units. Owing to the high water content of these mortars absorption rates into the unfired clay units are high and the sodium silicate content in the mortar effectively falls below 8 % and fails to give the mortar good strengths. Sodium silicate content is also effectively reduced in a joint thinner than 3 mm as the absorption rate of the sodium silicate into the unfired clay units is not affected and therefore good mortar bond strengths are still formed with the thinner joints but the mortar strengths are poorer due to lower than the 8 % sodium silicate concentrations required to give good mortar strengths.

At sodium silicate contents of 10 % and in particular 12 % the clay mortars are more flexible and safeguard against problems encountered on-site giving security in construction and eliminating variability. Sufficient sodium silicate is available at these concentrations to compensate for thinner joints avoiding problems resulting from irregularities on the surface of the bricks, poor tolerances and irregular sizes of inert particles in the mortar. Variability in water contents, sand contents, shape and size of sand particles, clay content and coarseness of the brick clays are also eliminated. At 12 % sodium silicate contents, the water contents of the mortars are readily adjusted to give low viscosity mortars suitable for application through dipping of the brick units or application using special tools. The substantially higher mortar strengths and mortar bond strengths at 10 % and 12 % sodium silicate contents potentially give walls of higher strengths namely when using unfired clay masonry units of higher strengths such as those extruded with soils of higher clay contents or those stabilised (i.e. mechanically refined and/or containing additives) to improve on strength of the unfired clay masonry units.

6.5 Properties of unfired clay masonry

The trial to produce the prototype unfired clay masonry units was only partly successful. Owing to problems encountered on the trial the unfired clay masonry units produced were sub-standard and those required to fully asses the influence of perforations and wood-fibre on the properties of the unfired clay masonry units and masonry were not produced. Solid block units and perforated block units both without wood-fibre were successfully extruded. Attempting to mix the wood-fibre into the clay created serious problems. Blockages occurred in various parts of the process and extrusion of the wood-fibre clay mixture was difficult. As a result, only perforated masonry units containing wood-fibre were extruded before the trial was terminated due to the blockages in the mixing and feeding stages and the extruder. An inconsistent clay/wood-fibre mixture was produced which made extrusion of the masonry units difficult. The masonry units produced were of varying wood-fibre contents, poor tolerances and of too high water content. Some meaningful results were derived from the prototype block units extruded.

Compressive strengths of the unfired clay masonry units were acceptable for the construction of non-load bearing walls. Strengths of the solid masonry units without wood-fibre were substantially higher than the 2.5 N/mm^2 required and those of the perforated units with and without wood-fibre were similar to the 2.5 N/mm^2 required. Flexural strengths of the masonry units were higher than that required in non-load bearing walls with the exception of the flexural strengths of the perforated masonry units with and without wood-fibre when loaded in the direction of extrusion (i.e. with perforations running parallel to the load plane). The toughness and water erosion of the perforated wood-fibre blocks were significantly better than the solid and perforated blocks without wood-fibre.

Masonry tests done on wall panels constructed from the prototype unfired clay blocks and a 12 % sodium silicate mortar applied by dipping or application tool gave good properties. Mortar bond strengths of the horizontal bed joints in the masonry were higher than the 0.2 N/mm^2 required for thin wall construction. Mortar bond strengths and failure modes were not typical of that observed from unfired clay mortars with 12 % sodium silicate contents. Scoop and dipping application of the mortar was gave rise to joints thinner than 3mm which did not cover and bond the entire surfaces of the masonry units together. Owing to the poor tolerances of the masonry units, the thin mortar joints and poor mortar coverage of the masonry units a number of failures were premature giving characteristic strength substantially lower than expected. Applying the mortar to ensure a 3 mm joint thickness gave substantially higher bond strengths than that required for thin wall construction (i.e. 0.4 N/mm^2).

Compressive strengths of the solid block and perforated wood-fibre block wall panels were higher than the 1.10 N/mm^2 required for low strength materials.

Compressive strengths of the perforated block wall panels without wood-fibre were significantly lower and not suitable for the construction of non-load bearing walls. Flexural strengths of the wall panels measured parallel to the horizontal bed-joints were all above the 0.2 N/mm^2 required. However, the flexural strengths of the wall panels measured perpendicular to the horizontal bed-joints were all significantly lower than the 0.4 N/mm^2 required.

The poor flexural strengths measured perpendicular to the bed-joints were directly related to the un-mortared perpendiculars. Mortaring of the perpendiculars substantially improved the flexural strength of the masonry perpendicular to the bed-joints. The improvement in flexural strength was not sufficient to overcome the poor flexural strengths of the perforated masonry units when loaded in this direction but would give the solid units without wood-fibre the flexural strength required for construction when loaded in this direction. It is speculated that with mortared perpendiculars and good 3 mm thick or even thicker (i.e. 5 mm) mortar joints to compensate for the poor tolerances and allow for the construction of well-ordered sound wall panels the flexural strengths would be substantially increased to give the required strength for the perforated wood-fibre block panels measured perpendicular to the bed joints. Owing to the low flexural strengths of perforated block units without wood-fibre in this direction, it is doubtful whether these wall panels will give the required flexural strengths with the thicker mortar joints.

Wood-fibre substantially improved the properties of the unfired clay masonry. Gross compressive strengths of the perforated masonry wall panels were substantially higher with the wood-fibre than without. Gross flexural strengths of the perforated masonry wall panels and perforated masonry units, with the exception of the flexural strength perpendicular to the bed-joints of the masonry, were substantially higher with the wood-fibre than without. Gross flexural strengths of the perforated wood-fibre masonry units and wall panels were higher than those of the solid masonry units and wall panels without wood-fibre. Goss compressive strengths of the perforated wood-fibre masonry units and wall panels were higher than that required for construction but were lower than that of the solid masonry units and wall panels.

A lighter, tougher and stronger perforated unfired clay masonry unit with more value than the dense, heavy solid unfired clay masonry units and weak perforated masonry units can be produced with the inclusion of wood-fibres. Wood-fibre blocks will better resist breakages during transport and handling, internal stresses that develop with the absorption of moisture during plastering, abrasion, water erosion and improve on screw fixing strengths.

An additional mixing stage and souring stage gave a homogenous clay/fibre mixture which extruded without any major problems. Wood-fibre at a 2 % content was successfully mixed into the clay using a pan mixture. The mixture was left to sour to stabilise or mature the clay and wood-fibre mixture and attain equilibrium moisture contents between the clay and wood-fibre, and improve workability. Unfired clay masonry units of good wet strengths were extruded without any problems. The tolerances of the masonry units were good and suitable for the construction of masonry using a 3 mm thick joint.

On consultation with the plant operators, it was confirmed that such a premix and souring stage would consistently give unfired clay masonry units of good tolerances and consistent wood-fibre contents. These stages are essential to ensure true masonry block units are produced and that well-ordered sound walls are constructed with improved compressive and flexural strengths. The poor tolerances in the masonry units without the wood-fibre in the previous trial was questioned as it was only the wood-fibre that caused problems leading to poor extrusion of the masonry units. It was concluded that this was due to operational problems and would not be the case if the block units were manufactured to the strict specifications required for clay bricks.

The research concludes that the extruded process is suited for the manufacture of unfired clay block units for the construction of thin-non load bearing walls. Wood-fibre at 2 % by dry weight content and perforations are beneficial and not only give good improvements in properties but also adds value to the unfired clay block units. A mortar containing a sodium silicate content of 8 % or higher manufactured from the respective brick clays and a joint thickness of 3 mm is suitable for the construction of the walls. It is recommended that higher sodium silicate contents be used to safeguard against problems on-site and to allow for quicker mortar application methods such as dipping and tool application methods. A 5 mm thick joint is also advisable to compensate for coarse particles in the mortar mixture, surface irregularities and poor tolerances on the masonry units.

The main advantage of the thicker 5 mm joint is the savings in cost and time. Mortars can be produced from the coarse brick clay sourced directly from the factory. Grinding of the clay to eliminate the coarse particles is not required. Such a thick joint at 12 % sodium silicate content ensures there is sufficient sodium silicate in the solution retained in the mortar after absorption of the solution into the unfired clay masonry units to give good mortar strengths and that there is sufficient sodium silicate in the solution absorbed into the unfired clay masonry units to give good mortar bond strengths. Straw can be added with the 5 mm joint without significantly interfering with the mortar strengths and bond strengths to reduce wastage of the mortar down the perforations.

The increase in cost of the thicker mortar joint (i.e. from 7.2 pence per metre to 12 pence per metre) would be offset by these savings in production cost. Cost for the 5 mm thick joint is approximately double that of the standard cement mortar 10 mm thick joint (6 pence per metre) but embodied carbon is substantially lower (0.07 kg.CO_2 per metre compared to 0.4 kg.CO_2 per metre). The added advantages and robustness of the 5 mm thick 12 % sodium silicate mortar joint makes the increase in cost and embodied carbon (0.04 kg.CO_2 per metre compared to 0.07 kg.CO_2 per metre) less significant.

6.6 Limitations of research

The limited timescale governed the outcomes of the research. The overall time allocated for the research was two years and only nine months was allocated to experimentation and testing to develop the unfired clay masonry system including renders and fixings. Owing to problems with the economy, sourcing of the materials and extrusion of the unfired clay wood-fibre masonry units the experimental stage needed to be increased to allow for additional testing to assess factors that were not predicted at the onset of the programme. This was necessary to formulate a prototype unfired clay block and mortar, and to develop a process to extruded the unfired clay block unit. Some of the testing initially envisaged was disregarded and additional series of tests were added to ensure the masonry unit, mortar and masonry fulfilled the basic requirements for the construction of non-load bearing walls, that is, with regard to compressive strength, flexural strengths and mortar bond strengths.

A poor economy at the time of conducting the research indirectly impacted on the outcomes of the research. The building industry showed no growth over this period and major cuts in the production of bricks occurred. This led to the closure of many factories in particular the specials plant ear-marked for the trial of the prototype block units. The specials plant produces lower volumes of irregular shaped clay masonry units and was ideal for trial required to manufacture the large dimension prototype block units. As a result, a complete series of mortar tests were re-done using clay and unfired brick units from a different factory were a specials plant was available.

Sourcing of the wood-fibre caused considerable delays as wood-fibre was not produced locally and needed to be shipped from mainland Europe. Wood-fibres were also wet and needed drying prior to shipping and such facilities were not available at the factory producing the wood-fibres. No problems were envisaged on obtaining the initial small quantity of wood-fibre for the trial to ascertain the advantages of the using the wood-fibre in the unfired clay materials. Drying times of the large amount required for a trial was substantially longer and delayed the running of the trial.

The extrusion process used to produce fired clay bricks is relatively straight forward but offers little flexibility to allow the addition of materials such as plant fibres into the brick clay. The problems associated with the extrusion of the wood-fibre mixture required an additional investigation into the mixing of the wood-fibre into the brick clay, the influence of the wood-fibre on the plasticity of the clay and souring of the clay to regain plasticity after the addition of wood-fibre. A soured homogeneous mixture was then extruded to see if a large quantity of unfired clay wood-fibre masonry units could be extruded.

Other limitations not related to the timescale of the research were those due to the properties of the unfired clay materials, restricted availability of the plant fibres in the UK, requirements of the industrial partner and problems associated with the trial.

Owing to the low compressive strength of unfired clay and the sharp reduction in compressive strength associated with the absorption of moisture, the research was limited to finding a masonry system for the construction of non-load bearing inner walls. A wall to give better performance would require modifications to improve on compressive strength and water resistance and limit the influence of moisture absorption on compressive strength. Such modifications may require additives that impact on the environmental elements of the unfired clay material such as giving them higher embodied energy and carbon and rendering them non-recyclable and non-degradable. These additives may also seriously impede the benefits such as indoor climate control achieved when using unfired clay walls.

An environmentally friendly and completely recyclable product which on disposal would have minimal impact on the environment was desired. The research was therefore limited to using natural additives such as the plant fibres used to stabilise and improve on the properties of the unfired clay.

Shortages of plant fibres in the UK, cost of fibres, cost and energy associated with transport/import of fibres and cost of processing fibres into the desired form limited the investigation and only straw, flax, hemp and wood fibre were considered. Wood fibre, which proved most suitable, was scarce in the UK and the wood-fibre needed to be imported from within the EU. A poor economy at the time of the research significantly restricted the availability of imported wood-fibre from the EU and sources which were available directly from the EU were unreliable. Straw lowered the compressive and flexural strength of the unfired clay masonry units rendering them unsuitable for the construction of thin non-load bearing walls. Hemp and flax were expensive and required further processing making them less cost effective than wood-fibre.

Owing to the problems associated with the mixing of the wood-fibre into the clay for the extrusion of brick units and the limited and slow supply of wood-fibre the research was limited to the comparison in the properties of only three different types of prototype unfired clay blocks instead of the six required to give a comprehensive investigation into the properties of the extruded unfired clay masonry units with and without wood-fibre and perforations. Any further trials to produce the prototype block units required first needed the formulation of a mixing and souring stage to obtain a homogenous clay/wood-fibre mixture to allow the extrusion of good quality unfired clay masonry units. The mixing of the wood-fibre into the brick clay could only be done off-site on a small scale and this prevented the further running of a trial to produce the block format envisaged for mainstream production.

6.7 Overall conclusions and future research requirements

Overall the project was successful. A feasible unfired clay masonry system was demonstrated from the results obtained from the three different block formats produced. A small scale trial to assess the mixing and souring of the brick clay and wood-fibre mixtures allowed successful extrusion of solid wood-fibre blocks which was used to construct a trail building that is showing good performance.

Strict quality control in the extrusion of fired-clay bricks would ensure the unfired clay masonry units extruded and mortars developed from these brick clays are consistent and easy to standardise. Manufacture of the unfired clay units and mortars are quick and construction of the unfired clay masonry is similar to that of concrete block and fired-clay brick masonry used for the mainstream construction of thin-walls in modern buildings.

At this stage perforated unfired clay block units containing 2 % wood-fibre and similar in size to concrete blocks seems feasible for the construction of non-load bearing thin walls using a 12 % sodium silicate mortar developed from the respective unfired brick clays and a 5 mm thick mortar joint. Certification and marketing of the unfired clay masonry can only commence once the prototype masonry satisfies all requirements for low strength materials used in the construction of thin non-load bearing inner leaf or interior walls. Once the unfired clay masonry format has been established and tested both in the laboratory and on-site the certification and marketing strategy can be developed and steps can be put into place to develop specifications and standards for such earth building systems to give them more value and enable them to compete with industrial building systems such as concrete block and fired-clay brick systems used in modern mainstream construction. A truly sustainable building is only possible with the use of natural building materials in their construction such as unfired clay, which possess low embodied energy, embodied carbon, and are renewable, recyclable and disposable, have low waste and impact on pollution. Such buildings will substantially lower the impact the building industry has on the environment and reduce the damage to planet earth imposed by the rigours of modern life.

The priority in the future must be to develop a mixing and souring stage at the factory to ensure continuous production so as to conduct more trials to finalise the format of the unfired clay masonry units such as shape and size of the block, shape and size of the perforations and the wood-fibre content. This is required to qualitatively assess the properties of solid and perforated unfired clay masonry units with different wood-fibre contents to those without wood-fibre, attain the required flexural strengths perpendicular to the bed-joints for the perforated wood-fibre masonry units and to develop a block which is easily manageable and robust enough to withstand the rigours of modern construction.

A reliable wood-fibre source is required to ensure successful production of the unfired clay masonry units. Importing the wood-fibre is a short term option. A more viable option is to manufacture the wood-fibre locally. A thermo-mechanical refiner is required preferably at the brick plant to produce the required wood-fibre at the brick plant. The wood-fibre produced could be fed directly into the mixing stage developed or possibly directly into the extruder, which will eliminate additional storage and drying of the wood-fibre. Alternative plant-fibres also require further investigation to possible reduce cost and alleviate scarcity.

A further investigation is required to refine the sodium silicate clay mortars and assess feasibility and properties of the mortars containing different sodium silicate, clay and sand contents, coarseness of clay and sand, plant fibre contents and mortar joint thicknesses. Altering or modifying the sodium silicate clay mortars to give cheaper manufacture, simplify application, less usage and less wastage is essential to achieve a mortar that gives the required strengths at the lowest cost and to minimise the overall embodied energy and embodied carbon of the masonry.

An investigation into the stabilisation of the brick clay, modification of the unfired masonry units and mortars to improve robustness, particularly water resistance without compromising environmental performance is necessary to allow the use of the unfired clay masonry in thin-walled load bearing applications.